Multidisciplinary Analysis and Parametric Optimisation of Box-Wing Aircraft for Reduced Fuel Burn

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Ishan Roy Salam

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Contents

Abstract

A conceptual design analysis methodology and toolchain was developed for multidisciplinary analysis of box-wing aircraft. This methodology was applied to investigate the effect of wing geometry variation on specific range for various short-range missions. The results were compared with an equivalent, cantilever wing aircraft to determine potential improvement over conventional aircraft designs. The multidisciplinary design analysis incorporated aerodynamic and structural optimisation methods and tools to explore the influence of key geometric parameters and mission requirements on the aerostructural characteristics. The aerodynamic and structural analysis and optimisation, via a design space exploration, was undertaken using vortex-lattice methods and finite element analysis tools developed or integrated in a common framework that facilitates rapid and easy data exchange.

This study shows that the geometric parameters of horizontal wing separation, vertical wing separation and aspect ratio are the key design parameters for the box-wing concept and their effect on aircraft performance was analysed in detail. To compare the performance improvement of the box-wing over its conventional counterpart, the same methodology was applied to the conventional aircraft, keeping total wing reference area the same. The wing area was used as the reference parameter as it is driven by take-off distance and would not be affected by cruise performance. The results show that horizontal wing separation should be minimised, and that lower vertical wing separation and aspect ratio for the box-wing led to improved fuel burn. The box-wing had higher structural efficiency with a lower aerodynamic penalty due to the reduction in induced drag that the box-wing offers.

To determine the effect of different missions on the box-wing performance, four different missions were analysed and compared, by varying cruise Mach number, altitude, payload and design range. The results indicated that for missions flown at slower cruise Mach numbers and lower altitudes

with smaller payloads, a fuel burn reduction of 5% can be achieved with the an optimal box-wing configuration compared to an equivalent conventional configuration.

It was shown that the box-wing configuration can be an improvement over its equivalent conventional aircraft configuration in terms of performance, but the fuel burn results are dependent on the mission criteria and the choice of geometric parameters. This indicates that the window of improvement is small and specific, but the box-wing holds significant promise for future development and should be the focus of further, detailed research and analysis.

Nomenclature

$\mathbf{A_{max}}$	The maximum cross-sectional area presented to the flow (m^2)
$\mathbf{b}$	Wingspan
$\mathbf{c_{HT}}$	Horizontal tail volume coefficient
$\mathbf{C_{D_0}}$	Subsonic zero-lift drag coefficient
$\mathbf{C_{D_{LP}}}$	Coefficient of drag due to leaks and protuberances on aircraft
$\mathbf{C_f}$	Skin friction flat plate drag coefficient
$\mathbf{C_T}$	Specific fuel consumption
$\mathbf{C_{Lmax_L}}$	Maximum lift coefficient during landing
$\mathbf{\bar{C}_W}$	Wing mean chord (m)
$\mathbf{D_h}$	Horizontal separation between horizontal wings of box-wing configuration (m)
$\mathbf{D_{ib}}$	Minimum induced drag of a biplane
$\mathbf{D_v}$	Vertical separation between horizontal wings of box-wing configuration (m)
$\mathbf{D_v/h_{f+t}}$	Vertical separation between the wings of a box-wing configuration expressed as a fraction of the height of the fuselage and tailplane
$\mathbf{D_h/l_f}$	Horizontal separation between the wings of a box-wing configuration expressed as a fraction of the length of the fuselage
$\mathbf{FF}$	Form factor of aircraft component
$\mathbf{F/F_C}$	The fuel burn by a box wing configuration for a particular mission compared to the fuel burn by the conventional configuration designed for that mission
$\mathbf{\left(\frac{L}{D}\right)_{CR}}$	Lift-to-drag ratio in the cruise condition
$\mathbf{M_{FF}}$	Mission fuel fraction
$\mathbf{R_{CR}}$	Cruise range (m)
$\mathbf{S_{HT}}$	Horizontal tail area (m^2)
$\mathbf{S_{LFL}}$	Landing field length (m)
$\mathbf{S_{wet}}$	Wetted area (m^2)
$\mathbf{S_{ref}}$	Reference area (m^2)

$\mathbf{\frac{t}{c}}$	Thickness-to-chord ratio of the airfoil
$\mathbf{V_a}$	Approach speed during landing (m/s)
$\mathbf{V_{CR}}$	Cruise speed (m/s)
$\mathbf{V_{SL}}$	Landing speed (m/s)
$\mathbf{W_{TO}}$	Take-off weight (N)
$\mathbf{W_L}$	Landing weight (N)
$\mathbf{W_F}$	Weight of fuel (N)
$\mathbf{W_P}$	Weight of payload (N)
$\mathbf{\left(\frac{W}{S}\right)_{SL}}$	Wing loading at landing (N/ m^2)
$\mathbf{\left(\frac{W}{S}\right)_{TO}}$	Wing loading at take-off (N/ m^2)
$\mathbf{\left(\frac{x}{c}\right)_{max}}$	Chordwise location of the maximum thickness of the airfoil
$\mathbf{\Lambda_m}$	Sweep of maximum thickness line (degrees)

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1. Introduction

1.1. Context

The civil aviation industry faces a number of challenges in the medium to long-term future that need to be addressed in order to ensure its sustainability (Cheze, et al., 2011). An average annual increase of 5% in demand for passenger traffic puts pressure on environmental impact and cost. For example, Bows (2010) outlines the necessity of reducing carbon dioxide emissions from aviation in order to meet reduction targets set by advisory and regulatory bodies. Owen, Lee and Lim (2010) show that aviation emissions are predicted to grow to 2050, due to growth in traffic in economically-developing sectors like Africa and Latin America. Sgouridis, Bonnefoy and Hansmann (2011) emphasise that several key improvements in technology and operations are required to sustain passenger and cargo mobility growth while reducing emissions, as without them emission levels become uncontrollable. Concurrently, future oil production is forecasted to decrease, leading to a possible shortage in jet fuel supply and increasing prices (Nygren, et al., 2009).

Several international organisations have set specific and challenging targets. For example, The Advisory Council for Aeronautics Research in Europe (ACARE) sets some objectives in its *Flightpath 2050* report, including 75% reduction in carbon dioxide emissions per passenger kilometre by 2050, relative to 2005 levels (ACARE, 2011), building on targets set earlier of carbon-neutral growth from 2020. Similarly the International Air Transport Association (IATA) has also set goals of carbon-neutral growth from 2020, and a 50% reduction in carbon dioxide emissions by 2050 (IATA, 2009).

Such ambitious goals will not be met by gradual and evolutionary technology improvements. Lee et al (2009) shows that substantial emission reductions can only be achieved by the introduction of new and radical technologies and designs. Quantum-leap improvements in technology need to be allied with new solutions that break away from the current conventional design paradigms (Mistry, et al., 2007).

While there are several approaches that are currently the focus of research and design efforts around the world including laminar flow technology, new engine and fuel types and multi-stop operations, one possibility that is very promising is the use of unconventional wing configurations such as the blended-wing-body (BWB) arrangement, or the C-wing arrangement (Kroo, 2001). These aircraft configurations show potential structural or aerodynamic improvements over the conventional planar wing configuration.

One of these unconventional configurations that is being investigated is the box-wing, which consists of two horizontal wings joined at the tips by vertical winglets that run from the bottom wing to the top wing as shown in Fig. 1-1. The advantages of this configuration have been known since the 1920s, based on the work initially done by Ludwig Prandtl and Max Munk. Munk concluded that the best way to reduce the amount of induced drag produced due to the velocity of the free vortices was to have this system involving vertical and horizontal wings (Munk, 1921), which Prandtl then built on with his ‘Best Wing System’ where he proposed that a multi-wing configuration with equal total lift distribution on both wings and a certain lift distribution on the vertical winglets would be the most efficient wing planform for reducing induced drag (Prandtl, 1924).

Figure 1-1 Box-Wing (Frediani, 2005)

Despite the fact that the theory behind the box-wing has been known for some time, the concept itself remains relatively unexplored in terms of design knowledge and understanding. The interaction between aerodynamics, structures and other aircraft characteristics as a function of basic geometry parameters are not that well codified. This in contrast to conventional configurations, which are extremely well understood and have the underlying theory as well as data available from historical and statistical data to correlate and validate said theory. This makes it a much safer and easier option to pursue when considering any particular mission profile or request for proposal. Hence to lower the barrier to entry for choosing the box-wing concept, a level of understanding must be reached that allows the designer to be comfortable in working with the concept and pursue it going forward when handed a suitable set of mission requirements.

1.2.Problem Definition

The key problem with regards to the box-wing and its application is that a lack of understanding and knowledge exists about its multi-disciplinary behaviour as a complex system and the effect on performance.

Part of that lack of understanding is the relationship and the interaction between the aerodynamic and structural influences on the design. These two disciplines drive the performance and weight of an aircraft configuration. Further lack of data exists in terms of deciding which kinds of missions, and what sort of performance requirements the box-wing is best suited for and where it might deliver superior performance and environmental outcomes compared to the conventional aircraft.

While the aerodynamic theory behind the box-wing has been well-understood, less well-known is the influence of various geometric parameters on performance-related characteristics. Theoretically the vertical separation is supposed to be a bigger driver than the horizontal, but to what extent for any particular configuration or design has not been quantified for example. Understanding the behaviour of key performance characteristics such as induced drag and lift accurately, at least at a pre-design level, is absolutely foundational for any reasonable and usable sketch of the design space of a box-wing aircraft to emerge for further use.

Similarly, for structural design knowledge- the wing weight is a key and crucial component in understanding the strengths and weaknesses of any conceptual configuration, but there is a lack of knowledge with regards to how it is affected by particular design requirements for a box-wing, and how the unique structure of a box-wing drives the wing weight to particular values for different configurations and geometric changes. Another area of concern is that many of these design studies focused on one specific configuration or a specific combination of geometric design parameters, and then heavily analysed that configuration using computationally-intensive, high-fidelity tools and methodology. However at the pre-design and conceptual design stage, this is not a helpful course of action, and the data provided is not useful. What is required is a broad range of data that covers a much larger design space that can then be used to narrow down the range of possibilities to suit a particular set of design requirements. This offers flexibility and utility that is not present with a single design that is very highly detailed. Secondly a methodology is established to draw out that large design space in a relatively rapid and controlled manner, allowing for future explorations of a box-wing design space with different configuration-types or parameters to be done relatively quickly and in a straightforward manner by following the guidelines. The trade-off for a larger design space in a time and manner that is not too intensive is that the results will necessarily be of lower fidelity, however that is an acceptable compromise and a well-established method of conducting these types of parametric studies with regards to conventional configurations in the field of aircraft design.

Beyond that, very little data exists that combines the necessary outputs of these two disciplinary analyses into an overall design space and assessment of the box-wing, which is an absolutely necessary and critical requirement for gaining a deeper understanding of the box-wing and eventually presenting it as a viable alternative of conventional configurations. Aircraft design is in itself a multidisciplinary design task, with little value to aerodynamic or structural analysis done separately as design decisions and choices need to be made that take into account the various weightings and advantages and disadvantages each choice has from each of those disciplinary perspectives. Hence the interaction and interplay between primarily those two disciplines, but also others such as stability, form an integral part of the knowledge base that needs to be established for the box-wing. Traditionally those two have generally been at opposite ends of the spectrum, demanding designer engineers strike a balance between structural and weight concerns and optimum aerodynamic performance but the box-wing's unique blend of structural and aerodynamic properties may well change that entire paradigm of thinking.

Furthermore, specific box-wing design studies have generally focused on certain kind of aircraft- those that are very large, seating passenger numbers similar to the Airbus A380 for example. Given the paucity of data on the box-wing, any analysis that is done that is focused on such large aircraft cannot easily be transferred or scaled if the mission parameters are then reduced. On the other hand, box-wing aircraft design studies for smaller aircraft with mission-requirements sized to a use-case for short-range or city-hopper style missions are extremely thin on the ground. Looking at just one set of mission requirements or specifications is unlikely to provide a holistic picture of the design space of a box-wing aircraft, and whether it actually offers any performance or environmental advantages over the conventional configurations. Instead considering a variety of mission requirements that vary the specified parameters to cover a broader design space offer a much better chance of assessing the overall viability of the box-wing, and provides more information and data for future design engineers to draw upon if considering the box-wing for further detailed scrutiny for their particular requirements.

This particular lack of knowledge is a problem because there are elements to the box-wing configuration that seem naturally suited to such a mission. The induced drag reduction on offer from a box-wing configuration is of paramount importance more during short flights as it is larger part of the overall drag of the aircraft. Similarly the box-wing offers synergies in terms of low-speed flight as it is more aerodynamically efficient at lower speeds, also a major factor for short-range missions. Thus the lack of design knowledge for box-wing aircraft to serve as an alternative to the likes of Boeing 737 or the Airbus A3200, essentially, aircraft seating between 150 to 200 passengers, in terms of the mission specifications to be filled is a concern for any design study that seeks to tackle the configuration. Establishing where exactly the box-wing best fits in terms of possibly serving as a replacement for conventional aircraft amongst the various design niches and mission roles is a vital part of gaining an overview of the configuration and ensuring that more refined and detailed studies that take place in the future are aimed in a manner that makes the best use of their resources.

Finally, no analysis of an unconventional concept and the advantages and disadvantages inherent to it is complete without considering the best performance that can be extracted from a conventional configuration flying the same mission. In this case, the conventional configurations that fly the current short-range, city-hopper style scenarios should be considered, but also a hypothetical conventional aircraft designed to suit the particular mission requirements deemed fit for the analysis of the box-wing should also be considered. Often the lack of a suitable choice of aircraft for testing and comparison of the numerically-determined box-wing performance figures means there is a lack of reliability to the outcomes. Ultimately, the question of significance is whether a box-wing aircraft offers such a performance edge over conventional aircraft, while lowering the environmental impact of the flight, such that it becomes a desirable alternative for future aircraft designers.

Hence it starts becoming clear exactly what this particular problem with regards to the box-wing configuration is, and how it must be addressed. The lack of detail with regards to the design space in the pre-design and conceptual design process needs to be filled in somewhat, with both aerodynamic and structural disciplinary analysed required in order to understand how each functions individually. Then a multidisciplinary analytical approach that incorporates both and feeds them into each other to gain a solution that takes them into account needs to be found. However these analyses need to be focused in order to be aimed at a mission niche that has largely not been looked at with respect to the box-wing, that is the short-range or city-hopper concept aircraft, as it has synergies with the advantages of the box-wing that will be illustrated in greater detail further on. Multiple such mission requirements are the best way of assessing the overall viability of the box-wing in terms of how suitable it might be for any given set of performance requirements, and for exploring the behaviour of the design space. Finally there needs to be suitable comparisons made with regards to the outcomes of the analyses performed, in order to gain the best understanding of whether the box-wing concept offers a genuine alternative to conventional aircraft, and what kinds of improvements it might offer. These comparisons need to focus not just on current aircraft, but also on conventional configurations designed to the meet the specific design requirements such as that for the box-wing concepts. This then by and large defines the problem confronted in this particular study.

1.3.Purpose and Significance of Study

The problem definition leads to a number of research questions that must be addressed in order to understand whether the box-wing configuration offers a viable or even desirable alternative to the conventional aircraft configuration for the requisite mission niches- the short-range, city-hopper mission and the variable performance requirements that can fall within that description such as different cruise altitudes, passenger loads.

The primary purpose of this study is to assess the preliminary design space of a box-wing aircraft for short-range missions and to understand which missions requirements best suit the strengths of the box-wing configuration, and what kind of performance and environmental improvements it offers over the conventional aircraft in a qualitative and quantitative sense for a given set of mission requirements. To address these questions, requires the establishment and validation of a methodology to conduct relevant analyses to improve the understanding of the behaviour and performance of the box-wing configuration and build a platform from which further, detailed studies can be conducted.

Specifically this study focuses on the design and analysis of a 150-200 seat box-wing airliner which was optimised for minimum fuel consumption for several different mission scenarios and evaluated against equivalent conventional configurations designed for the same scenarios. An assessment was carried out on the performance and environmental benefits of using the box-wing configuration for short-range missions, and followed by conclusions and recommendations for further studies and research.

The study will focus on numerical and computational analysis, using both low and medium-fidelity methods as well as statistical and historical data (for conventional aircraft) and will validate results as best as possible against current aircraft and other studies of unconventional configurations.

Unfortunately wind-tunnel or other practical testing and validation lie beyond the scope and purview of this work.

The significance of the study lies in the fact that no such design study with regards to the box-wing configuration has been conducted and published, meaning there is a specific and vital gap in the knowledge base that needs to be filled with respect to the preliminary design and analysis of box-wing aircraft for short-range missions. Having this information at hand will allow further, more concerted research into the box-wing to focus on the most promising areas and will possibly serve as one step into one day turning the box-wing into a viable and necessary counterpart at the design stage to the conventional wing planform aircraft for design engineers in this field. Hence it will be of most interest not just to academics and fellow researchers, but in the long run also to industry and those in charge of ensuring that the lofty environmental goals outlined at beginning of this chapter can be and are met as best as possible.

Furthermore the method used in this study will also serve as a baseline and guide for future studies to be conducted in the same vein, perhaps with different scenarios or missions or combinations of geometric parameters, establishing the box-wing as a possible choice in future design studies by enabling engineers and designers at the preliminary or pre-design stage to quickly and broadly consider this configuration right alongside the conventional one when undertaking initial overviews of the available solutions to any aircraft design problem presented to them. Like the results, it is forecasted that the methodology will also be built upon and improved by future endeavours along this field, which will increase its robustness and make it more trustworthy.

Hence both the results and methodology are of significance, and the need for the study to be conducted given the gaps in the knowledge in this particular field is eminently clear.

2. Literature Review

2.1.Unconventional Aircraft Configurations

As outlined briefly in the previous chapter, unconventional aircraft configurations are being rapidly seen as being parts of the possible solutions to the complex and myriad problems facing aircraft designers and manufacturers in the coming decades. However, the design and analysis of these relatively unknown configurations proves for a challenge of its own which must be overcome before these configurations can be seriously considered as alternative to the conventional configuration.

The development of these kinds of configurations require the understanding of how they behave in comparison to conventional aircraft, what kinds of advantages and disadvantages they offer, the missions they suit and the problems they are most likely to help tackle. Increasing efficiency and reducing environmental impact of the air travel is certainly one area in which they have come to the fore (Mistry, et al., 2007). For reduction in drag-due-to-lift, a number of wing planforms were studied by Kroo (2001), which led to the following comparison of Oswald efficiency factor (a measure of how efficient each wing plan form was in terms of lift produced versus drag induced) as shown in Fig. 2-1.

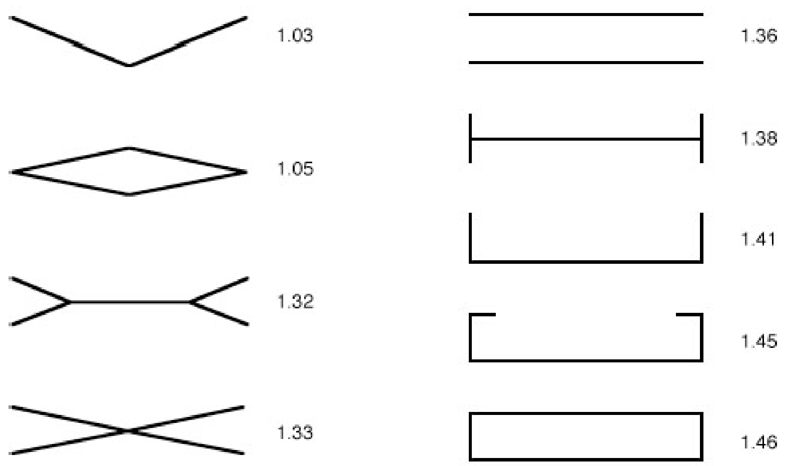


Figure 2-1 Oswald efficiency factor comparisons for different wing configurations (Kroo, 2005)

This comparison shows that not just the box-wing, but other innovative configurations such as the C-wing and the joined-wing are to be considered as possible solutions to the problems faced by the aircraft designers of the future. These all offer improvements in the lift-drag efficiency that could prove vital. Furthermore, other innovative designs such as the blended-wing-body and the circular wing also bring theoretical improvements and efficiencies to the table that should be considered further.

However, these unconventional configurations also pose a number of challenges in terms of design and analysis that must be met before they can be considered as realistic solutions. Primarily, aircraft design has been a historical process of evolution with reliance on past works and methodologies, which lead to statistical data and figures of best fit (Roskam, 2005), (Torenbeek, 1976) that are then used in process of conceptual and preliminary design for new aircraft. The complexity of aircraft as pieces of engineering, and the need for safety and reliability being a primary concern, has led to a process where almost all tools and analytical methods are predicated on past knowledge and experience.

Unfortunately, these tools and analytical methods are then not applicable when it comes to unconventional designs (Wolkovitch, 1986) as the different aerodynamic and structural behaviour of the aircraft means it does not follow the empirical rules and methodologies that have already been developed. Hence tackling these kinds of designs forces the designer to first develop and validate new tools and methodologies that can then be relied upon to firstly analyse the new aircraft configurations, and then deliver outcomes which can be used to compare them to current and predicted conventional aircraft.

This is especially important in the conceptual design stage of the aircraft design process. This stage is an essential part of the process, where the first step from a set of requirements to actual type of aircraft is made. Crude yet reasonably accurate estimates of performance data relevant to multiple disciplines of aircraft design such as aerodynamic performance, structural weighs and stability must be available to the design team (Piperni, et al., 2007). However, because some designs must be rapidly assessed and discarded so the team can focus on the most fruitful and likely to be successful configurations to take to the preliminary design stage, highly computationally-intensive analyses that may offer a high level of fidelity that cost a lot of time and money are not necessarily the correct way forward. Instead tools that quicker and easier to run that offer coarser data over a broader design space that allows the team to focus their efforts on the most relevant and likely solutions to the problem at hand, with higher-fidelity tools used rarely on an as-needed basis (Alexandrov, et al., 1999), are the most efficient way forward. Development of these tools forms a significant stumbling block in terms of unconventional configurations becoming a viable option and solution to design teams considering new missions and requirements for aircraft.

Another unique challenge posed by unconventional configurations in particular is the interplay between different disciplines of aircraft design, such as aerodynamics and structures. Much more so than in conventional aircraft, these and other disciplines are often intertwined in such a way that designing separately and linearly for each discipline in turn is not approach that should even be considered. This means that multiple disciplines must be evaluated at the same time, and their effect overall must be considered when making design decisions for these kinds of novel configurations. Multidisciplinary optimisation analysis (MDA) and optimisation (MDO) has now become an accepted part of the process of aircraft design (Sobieszczanski-Sobieski & Haftka, 1997), but their utility is manifestly greater when considering the likes of the box-wing or blended-wing-body design and indeed absolutely demands it (Livne, 2001).

However, a weakness of quite a bit of the literature and research done in this area is that because unconventional designs are often difficult to analyse, the design space is not chosen appropriately. In fact, in many studies a particular configuration and a set of parameters are chosen first often without reason or justification, and then analysed and optimised using high-fidelity MDO methods. The large region of the probable design space is rarely explored in order to ascertain what the best combination of those basic parameters are, and whether right wing size or aspect ratio or vertical separation or the like has been used (Rasmussen, et al., 2009). This is especially necessary when conducting conceptual design studies that look to compare and contrast unconventional configurations against each other and against conventional aircraft for the same mission requirements (Rohksaz & Selberg, 1989).

A further challenge when considering unconventional designs lies in the fact that certain configurations are more suited for certain mission concepts and requirements than others, and that the advantages of a particular configuration might outweigh its disadvantages for a particular mission but might not for another mission. Hence the evaluation and analysis of these concepts must be undertaken carefully with the right missions used for that particular concept (Kroo, 2005). For example, lift-induced drag is a larger concern with shorter-range aircraft as it is a larger drag component for the take-off and landing portions of the flight. In missions with long cruise segments, on the other hand, minimising parasite and wave drag is more important (Kroo, 2001). Some studies that seek to analyse these unconventional concepts unfortunately miss these kinds of necessary synergies between the type of mission and the chosen aircraft to be analysed, resulting in unsuitable results or outcomes which were somewhat predictable right from the start (Frediani, et al., 2003).

One study that did consider the effect of size and mission requirement on non-planar configurations (Jansen & Perez, 2010) noted that different types of non-planar configurations are suited to different kinds of missions. In particular, the joined-wing configuration was most optimal for short-ranged missions, while the best configuration for long-range missions was the C-wing. Alternatively, another study that considered C-wings against winglet designs for conventional wings found the latter to be superior once viscous drag and wing root bending moment was taken into account (Verstraeten & Slingerland, 2009). However, none of these studies considered the box-wing in particular, meaning there is a lack of data about the box-wing and where it might be most useful.

2.2.The Box-Wing

The box-wing (or Prandtlplane) design concept essentially began with the man after which it was eventually named, with Ludwig Prandtl's (1924) work on the induced drag of multiplanes. Prandtl proposed that the 'Best Wing System' (as he named it) was the most efficient lifting configuration, as it reduced the induced drag generated due to lift. This in turn was based off Munk's theory of minimum induced drag (1921) which was initially based on biplane wings and how they performed, and extrapolated out to the box-wing configuration.

Munk showed (1921) that the velocity of the free vortices induced at the ends of wings that are vertical are zero, while the ones induced at the end of wings that horizontal are constant. Prandtl builds on this with the Prandtl-Munk biplane theorem (Prandtl, 1924), stating that a number of conditions must be met in order for that to be true, including the fact that the total lift on both wings must be the same, and the lift distribution must be identical too. This derivation is show in Prandtl (1924) where the induced drag of a biplane is calculated by:

$$\mathbf{D_{ib}} = \frac{\mathbf{1}}{\mathbf{q\pi}}\left(\frac{\mathbf{L_1^2}}{\mathbf{b_1^2}} + \frac{\mathbf{L_2^2}}{\mathbf{b_2^2}} + \mathbf{2\sigma}\frac{\mathbf{L_1 L_2}}{\mathbf{b_1 b_2}}\right) \quad \textbf{(1)}$$

Here $\mathbf{q}$ is the aerodynamic pressure, $\mathbf{b}$ is the wingspan, $\boldsymbol{\sigma}$ is the coefficient of induced drag from one wing onto the other and $\mathbf{L}$ is the lift. At this point the total lift can be assumed to be the sum of the two lifts on each of the wings, and the ratio of the spans be $\mathbf{r}$.

If $\mathbf{L_2} = \mathbf{L_x}$ then

$$\mathbf{x} = \frac{\mathbf{r} - \boldsymbol{\sigma}}{\mathbf{r} + \frac{\mathbf{1}}{\mathbf{r}} - \mathbf{2}\boldsymbol{\sigma}} \quad \textbf{(2)}$$

Hence, the induced drag can be shown to be:

$$\mathbf{D_{ib}} = \frac{\mathbf{L^2}}{\mathbf{q\pi b_1^2}} \frac{\mathbf{1-\sigma^2}}{\mathbf{r\left(r+\frac{1}{r}-2\sigma\right)}} \tag{3}$$

The induced drag of a biplane is hence minimum when the $\mathbf{r}$ is at its maximum value of 1 (as it is a ratio). In this case, $\mathbf{x}$ becomes equal to 0.5 which is when lift is equal on both wings. In this case the expression simplifies to:

$$\mathbf{D_{ib}} = \frac{\mathbf{L^2}}{\mathbf{q\pi b_1^2}} \frac{\mathbf{1+\sigma^2}}{\mathbf{2}} \tag{4}$$

A butterfly-shaped lift distribution should also be present over the vertical wings at the same time, and this distribution can be seen in Figure 2-2. Frediani (2005) who picked back up on this work and brought the box-wing configuration to the fore again (while christening it the Prandtlplane), argued that this configuration was the most advantageous to the designer in terms of efficiency gains as long as these conditions were met. The efficiency is dependent on the size of the gap between the two wings, or more accurately, the gap-to-span ration for that wing configuration (Frediani, 2005).

The increase in lift-to-drag efficiency is hence due to the fact that the presence of a closed-wing system strongly inhibits the generation of wingtip vortices as the flow of air stays attached to the wing configuration more strongly rather than spinning out into the freestream at the tips of the wings and hence sucking out energy from the rest of the wing and hence ensuring that more overall lift needs to be generated to overcome that loss. This is the fundamental underlying principle of the box-wing configuration, and the reason it becomes so attractive to aircraft design teams. Induced drag is such a large part of the overall drag polar for aircraft that any significant reduction in it would be a major step forward for aircraft design in general.

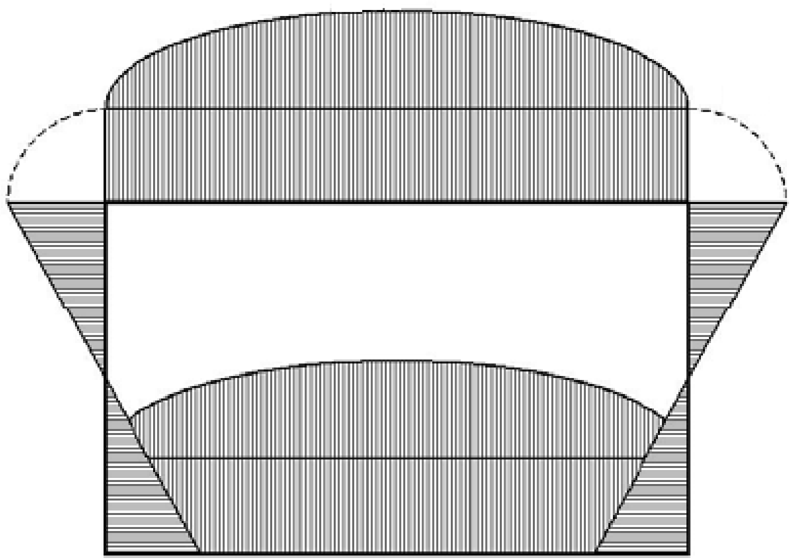


Figure 2-2 Theoretical lift distribution for box-wing (Frediani, 2005)

Lift for box-wing aircraft is simply a total of the lift generated by each wing separately and added together. However, these wings have considerably higher efficiency, as denoted by span efficiency or Oswald efficiency factor (*e*), than normal monoplane wings due to the reduction in induced drag offered by them. In fact for box-wing aircraft, the span efficiency factor can rise to well over 1 theoretically up to 1.5, whereas for conventional monoplanes it is restricted to between 0 and 1 (Wolkovitch, 1986). This assumes that the vortex sheet shed by the front surface remains undistorted and parallel to the freestream (Corneille, 1999), but there is a problem- the theory overestimates the actual findings in this case. This is due to the fact that Prandtl-Munk biplane theorem over-predicts the effect of the wash from the front wing on the rear wing, but due to the large stagger present this error becomes significant and needs to be rectified (Corneille, 1999).

Rohksaz and Selberg (1989) conducted a study into this area comparing the results predicted by theory from Prandtl (1924) to more accurate analysis method by vortex-lattice methods, and found Prandtl-Munk theory significantly over-predicting the lifting and efficiency gains from three-surface aircraft compared to a conventional layout. Importantly, they also found that a large three-surface aircraft was not as efficient as an equitable conventional aircraft (Rohksaz & Selberg, 1989).

One of the first serious studies into the concept of the box-wing airliner was conducted at Lockheed in the mid-1970s, for NASA (Lange, et al., 1974). The study looked at a transonic biplane concept, joined at the tips, to fly at Mach 0.95 for a range of 5000nm and carrying a payload of 400 passengers. It is clear that this mission requirement was for the sizing and design of a very large box-wing configuration. A parametric design space exploration was carried out, based on the Prandtl-Munk biplane theorem in the most part for the aerodynamics, while structural analysis was conducted using a primitive structural code which mimicked conventional configuration analysis for the box-wing layout. The findings were hence of questionable value, but did establish the validity of the box-wing as an unconventional wing configuration in need of further study. The basic outcome were that an equal ramp weight was predicted for the box-wing as compared to a conventional aircraft that would meet the same mission requirements, and that flutter would prove to be a large problem at the chosen cruise Mach number (Lange, et al., 1974). The recommendation provided for the study was for follow up research for a smaller box-wing aircraft with lower mission requirements is conducted, along with basic wind tunnel testing and the like, but this recommendation was never followed up on at the time. Lange (1988) later restated the case for the box-wing, especially for a mission that would steer it away from those flutter and aerodynamic issues, again recommending further research is conducted into the configuration.

However, in recent times thanks to the environmental and efficiency goals outlined earlier, the box-wing concept has come to the fore again as a possible partial solution to some of those challenges. In one study it is offered as a possible solution which has high risks but also high rewards in terms of significant reduction in carbon footprint and fuel costs (Fielding, et al., 2010), compared to a laminar flow aircraft and an airborne-refuelled concept. However, deeper understanding of the box-wing configuration is required and presented in an overview of the next few studies.

A recent simplified overview for medium-range box-wing airliners is provided by Schiktanz and Scholtz (2011), who attempt to summarize the geometric definitions of a box-wing configuration for determining its aerodynamic characteristics, and in particular assessing the induced drag which is one of the key necessary outcomes for determining the overall efficiency of the configuration. However, this paper takes a mathematical and statistical approach to building a conceptual design, relying on outcomes from other studies being reliable and combining them together. This approach could prove to be faulty as those formulae rely on understanding of aerodynamic and weight characteristics that were developed in line with conventional configurations. While this study should be applauded for its clear conceptual approach towards a medium-range box-wing airliner, the outcomes are rather dubious and not justified with further analysis via other methods such as finite-element or aerodynamic modelling.

Another study into the box-wing's structural characteristics did consider more developed analytical methods, including a finite-element analysis of the wing configuration (Jemitola, et al., 2013) as demonstrated in Fig. 2-3. Here a different approach is taken, with FE analysis being used to modify a conventional design approach in order to apply it to box-wing configurations. The conventional analysis equation chosen (Howe, 1996) was applied to a reference design of a medium-range box-wing airliner, which was designed in comparison to a reference conventional aircraft. Vortex-lattice methodology was used to generate the wing loading at the requisite performance levels. The results were used to derive a formula for estimating the mass of the wing configuration of a medium-range box-wing airliner, using regression analysis applied to the FE results in order to derive new coefficients for Howe's (1996) equation that could be applied to the box-wing airliner. The fore and aft wings were shown to use the same coefficients, meaning the aft wing would be slightly lighter than the fore wing for this configuration. However there were also some issues regarding the type of analysis undertaken here. First of all, the configurations chosen for the analysis (both the conventional and the box-wing) were of a limited scope, for a single mission of 4000 nm, covering a small range of geometric parameters (wingspan 32-34m, wing area 110-124 m^2 etc). This means the analysis and the equation derived are only fit for that small window of parameters, and do not consider the wider design space most engineering teams would need to consider when choosing a configuration. Furthermore, there was no attempt made to consider the effect of multiple aerodynamic load cases, and the need to redesign the wing in order to optimize after every loop of the structural modelling. However, this study does establish the need for FE modelling to accurately capture the structural behaviour and analysis of a box-wing model, and provides an example of how the box-wing can be analysed next to a conventional configuration for the same mission.

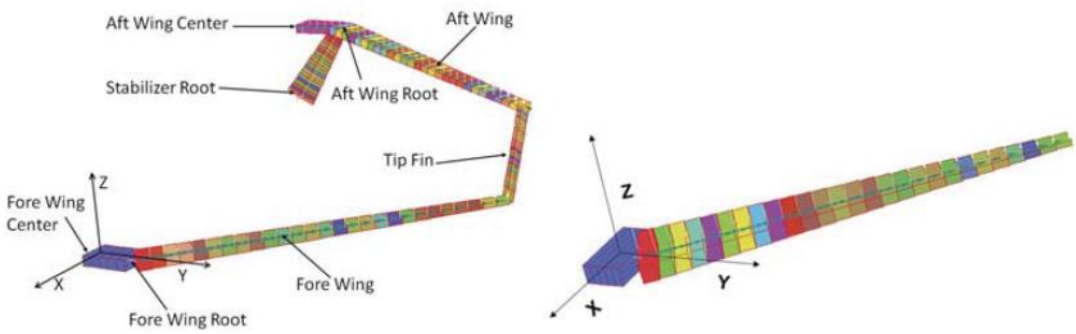


Figure 2-3 Comparison of FE models for box-wing and conventional cantilever configuration (Jemitola, Monterzino & Fielding, 2013)

One of the major recent studies on the box-wing concept has been the work done by the Italian universities consortium on a Prandtlplane design (Frediani, 2005; Frediani et al, 2003) has focused on a very large design aircraft concept to compete with or replace the Airbus A380 which is shown in Fig. 2-4. This design is a twin-fin concept, with a single-deck massive fuselage, with clean wings, with less friction drag due to theoretically much lower Reynolds numbers meaning laminar flow over the wings for much longer.

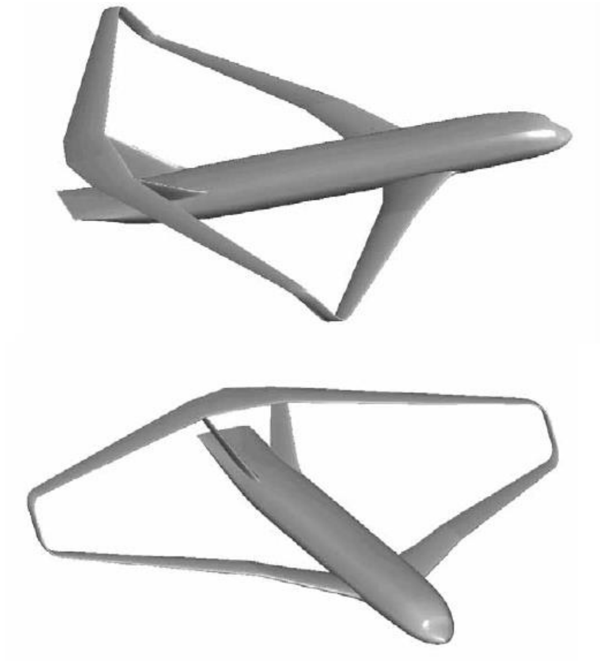


Figure 2-4 Very Large Prandtplane concept (Frediani et al, 2003)

The analysis of the design included CFD and FEM, and concluded that this design was feasible and worth pursuing further. As part of the same project, an ultra-light model Prandtlplane was built and tested with encouraging results (Frediani et al., 2007), leading to bigger model to be built for further testing for more accurate results. This work led to a number of spin-off studies into the box-wing, with the overall number of papers being the only comprehensive investigation into the box-wing concept in recent years.

Iezzi's (2006) work on high-lift devices was useful for only a limited number of wing configurations, while Bottoni and Scanu (2004) alternatively presented a design for a smaller box-wing aircraft. Bottoni and Scanu's (2004) work on designing a 250-300 seater Prandtlplane aircraft, flowing on from the work done by Frediani and others outlined, again developed an aircraft geometry, and designed it in comparison with the Airbus A330-200 and the Boeing 767-200. Here some of the conceptual design work was done almost after-the-fact, having decided on geometry and then tweaking it for benefits, rather than deciding on design features or key design drivers to pursue and designing around them. The authors also do much of the preliminary design analysis after building

CAD and CFD models, which seems to be the reverse of the logical order. However the design concept once again shows great promise and definitely warrants further investigation and research. Better conceptual approaches would allow designers to understand the advantages and disadvantages inherent in the concept, and allow them to harness the best features in an appropriate and beneficial manner.

One of the greater conceptual problems with these investigations is the fact that for large aircraft with large ranges and long cruise distances, induced drag becomes significantly less important than friction or zero-lift drag, meaning that crucial advantage offered by the Prandtlplane in non-cruise flight (when induced drag is at its most substantial magnitude) is negated relative to flight time and fuel burn in cruise. Hence of large aircraft in long distance flight, it makes relatively little sense to consider the box-wing from an aerodynamic efficiency perspective unless the efficiency gain in cruise is large in magnitude.

There are some alternative configurations and usages for the box-wing concept proposed in a later study (Frediani, et al., 2012), including an unmanned aerial vehicle (UAV) configuration, an ultralight configuration, an executive aircraft concept, an alternative that incorporates liquid hydrogen propulsion and a freighter variant. While the box-wing does have some appeals for some of these concepts, overall there are few detailed studies to support the development of the box-wing into aircraft to fit these niche mission requirements. For example, the major benefits in drag reduction offered by the box-wing are of little value for ultralight or light sport aircraft as the fuel usage and wing loading is so low that reducing the induced drag has little effect on the operating cost of the aircraft (Frediani, et al., 2012). Hence the actual mission scenario chosen for the box-wing configuration, in terms of analysis and comparison to a conventional cantilever configuration, needs to be very carefully considered in order to take maximum advantage of its strengths and minimise its weaknesses.

NASA Environmentally Responsible Aviation (ERA) Program

One of the major box-wing research projects currently on-going is part of a larger NASA research program on Environmentally Responsible Aviation (ERA) otherwise known as the N+2 project, looking at technologies for aircraft entering into service in 2020+ (Collier, 2012). There are number of companies participating in this project, which focuses on noise, fuel burn and cost reductions for future aircraft design by considering advanced multidisciplinary concepts and technologies that can be applied to single and twin aisle reference configurations. The three main concepts chosen for further development and analysis include a box-wing proposal put forward by Lockheed-Martin, which is intended to improve structural and aerodynamic efficiency (Mangelsdorf, 2011). An artist’s rendering of the concept is shown in Fig. 2-5.

Figure 2-5 Lockheed-Martin box-wing concept (Mangelsdorf, 2011)

Stated goals include incorporating advanced technologies in the areas of propulsion, materials, wing aerodynamics and airport handling and integration (Mangelsdorf, 2011). A presentation made by the Lockheed-Martin team on this project presented a basic overview of the methodology employed- here a mission requirement for 224 passengers being carried over 8000 nm is used to the design the aircraft, which may not be the most suitable mission for the box-wing (Martin, 2012). Fig. 2-6 illustrates the size and engine placement of the initial concept design.

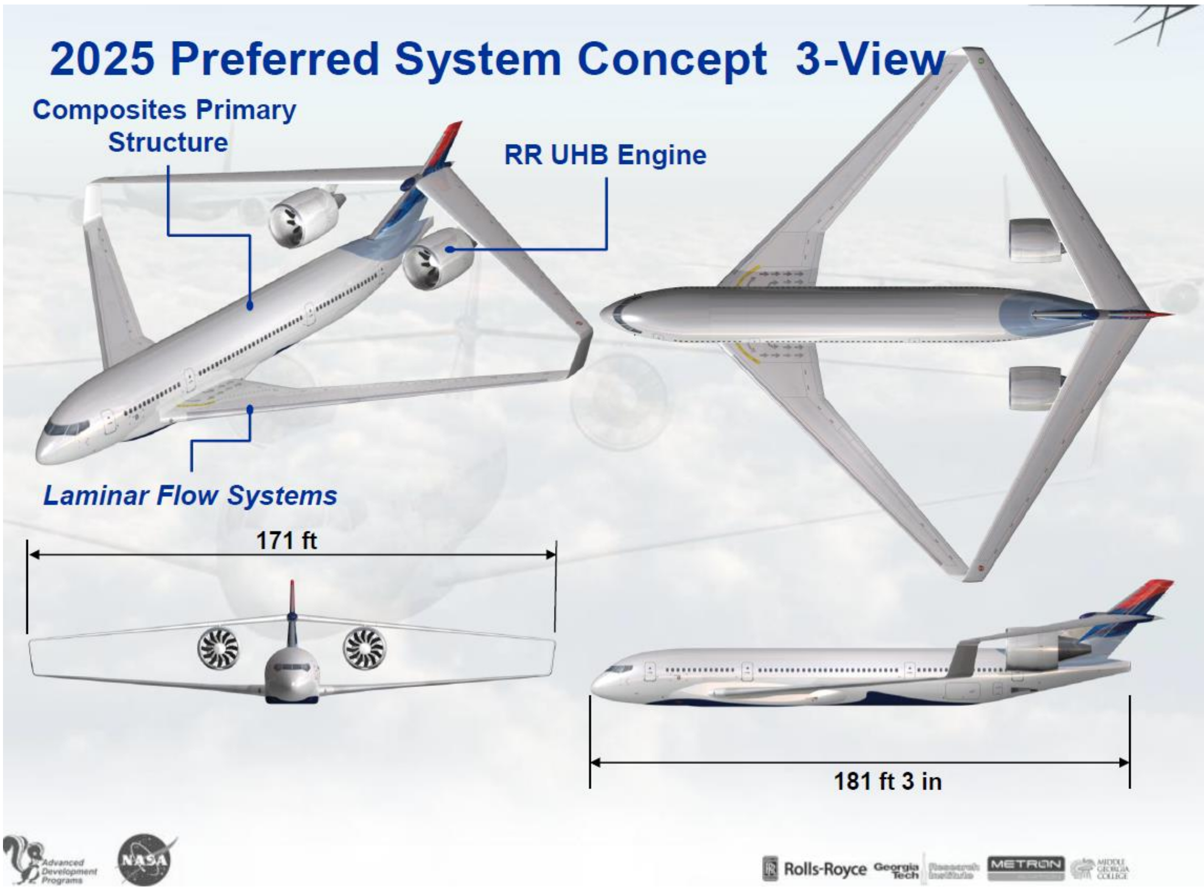


Figure 2-6 Preferred System Concept (Martin, 2012)

One of the key things to note is the methodology used for the Lockheed concept, where for the same mission the box-wing concept was developed and compared to a conventional concept also developed for the same mission plan using the same tools and subject to the same analysis. In many other studies such as the ones by Frediani et al (2012) or Shiktanz and Scholz (2011), the box-wing is compared to existing, outdated aircraft or sized to a mission designed for such an aircraft. The latter doesn't capture accurately the improvements offered by the box-wing, or does not allow the box-wing concept to be designed with its own strengths and weaknesses in mind. Lockheed Martin developed both the box-wing and the future conventional aircraft side by side for the same misison profile. In terms of their results, the box-wing concept did not show an improvement in fuel burn over the future conventional aircraft for this mission, but it does show an improvement in noise reduction (Martin, 2012). This could be due to the fact that the box-wing is not best suited for the mission requirements at hand for this particular study, especially tthe range and the Mach number in particular.

Martin (2012) also covered are some of the advances in key disciplinary technologies that would be required to make the box-wing concept a reality, and make sure those numbers presented, in terms of fuel burn and reduced acoustics, would become accurate. One such discipline is propulsion, where a next-generation ultrafan (a geared turbofan concept) was shown to be required as a key driver for this concept (Martin, 2012). Acoustics and a proof-of-concept vehicle that was being designed were also presented. This major study is still ongoing and shows that a box-wing concept is viable alternative based on the results so far (Martin, 2012).

The research studies presented so far show how important it is that the box-wing continues to be investigated for different mission profiles and using interdisciplinary methods of analysis, so a larger overall picture emerges of the concept that can be considered reliable and more useful for future designers.

2.3.Disciplines

Aerodynamic analysis is a key foundation stone in any study considering the box-wing concept, as it covers the advantages offered in terms of reduced induced drag that makes the box-wing an attractive configuration (Kroo, 2005). However, as the literature review shows (chapter 2), earlier studies considering the box-wing configuration utilised Prandtl-Munk's Biplane theorem which is inaccurate and tends to over-predict the improvement in induced drag. This means that other methods must be used for undertaking the aerodynamic analysis of this concept.

The primary aerodynamic qualities of interest here are the lift generated and drag produced when the aircraft is flying under certain conditions as specified by the mission requirements. Since induced drag is the main component of drag that is affected by the use of a box-wing configuration, any aerodynamic analysis has to consider it (Frediani, 2005). The lift-drag ratio is an important parameter determining aerodynamic efficiency of the box-wing over the conventional planform.

There are two possible pathways for the computational assessment of the box-wing concept under a certain set of mission parameters. One is to utilise coarser, lower-fidelity approaches such as vortex-lattice methods (VLM), while the other is a higher-fidelity, more computationally-intensive pathway such utilising computational fluid dynamics (CFD). The former is quicker and takes less computational time, and does not require strict control over configuration geometry and meshes. The latter offers more complete results, takes into account more forms of drag but also means that fewer geometries and a smaller area of the design space can be investigated in the same amount of time and effort. Use of these computational methods is required as the aerodynamic behaviour of these unconventional configurations such as the box-wing is not easily predicted using historical or statistical methods, and a certain degree of basic confidence is required in the results so that the analysis and requisite conclusions are reliable.

For conceptual design, VLM is generally the more suitable choice, and indeed many conceptual aircraft design studies use it (Jemitola, et al., 2013), (Mamla & Galinksi, 2009), especially for the box-wing aircraft. For detailed design studies on one particular set geometry and configuration which is to be analysed in detail, CFD analysis is more often used (Rasmussen, et al., 2009), (Rallabhandi, et al., 2001).

This study primarily considers the conceptual design of a box-wing aircraft and considers a broad design space, therefore VLM analysis of the aerodynamic characteristics of the configuration is the most suitable approach. Several different conceptual design studies have utilised this methodology, looking at various different unconventional configurations. For example, VLM was used in a design study of fire-fighting aircraft and their configurations, for assessing the aerodynamic qualities of the design including the lift and drag generated (Goraj, et al., 2001). The drag prediction here is especially important due to the kinds of missions and geometry profiles necessary for fire-fighting aircraft as the scoops for water intake and the short loops for firefighting and refilling mean the aircraft's drag profile is significantly different to other, conventional aircraft. Similarly, the box-wing has unique geometry and might be suited to different missions than current conventional aircraft, hence this study is particularly analogous to the box-wing configuration.

It was also used in an optimisation study considering a family of multiple blended wing body aircraft, which established how VLM was both powerful and efficient when considering a broad design space for another unconventional configuration (Willcox & Wakayama, 2003), as this study looked aircraft configurations for different sets of mission requirements. A study considering the design optimisation and drag polar of a joined-wing planform, another non-planar configuration, also utilised VLM as the most appropriate methodology (Rallabhandi, et al., 2001). The box-wing specifically was considered by a study that looked at an ultra-light configuration and used VLM for analysis of a box-wing to fit that purpose (Frediani, et al., 2007).This particular study developed scaled-down flight-test models from those designs and flew them, garnering performance that was similar to what was predicted by the VLM computational analysis. Another box-wing design study that also used VLM for the aerodynamic analysis is Jemitola et al (2013). Here the analysis was largely focused on the structural discipline, but the wing loads necessary for the structural modelling were derived using VLM.

While VLM is useful for analysing the aerodynamic characteristics of a non-planar configuration including lift and induced drag, one of the shortcomings it has is that the overall drag of the configuration is not calculated. This is because the zero-lift drag is not predicted by VLM, and must be analysed separately from the lift-induced drag. Wave drag, which is caused by shockwaves forming the wings as the aircraft approaches transonic speed, is also not analysed by VLM as compressibility effects are not taken into account. However if the analysis is for Mach numbers below 0.8, this is not a significant problem.

Zero-lift drag has three primary components. The friction drag is the resistance on the aircraft from moving through air, and is directly related the area that is exposed the airflow. This drag arises from the boundary layer transition from laminar to turbulent as the air flows down the length of the body, and viscous drag that henceforth occurs. Interference drag is the extra component of drag that results from the disturbance in the airflow at places on an aircraft of body where two profiles meet, such as a wing and the fuselage, or the wing and the vertical wingtip for a box-wing. Form drag arises from the resistance of the shape or profile of a body moving through airflow. The larger the profile and the more of it is that is presented to the airflow, the greater the amount of drag generated. Also, moving at higher speeds will lead to higher amounts of profile drag (Roskam & Lan, 1997).

These components can be difficult to analyse for box-wing aircraft without resorting to CFD methods (Bottoni & Scanu, 2004), and generally the best approach is to utilise a drag build-up method as undertaken for conventional aircraft, and then modify that further with a margin of error when taking into account the greater chances of interference, surface area, profile drag etc. arising from the box-wing configuration (Frediani, 2005). This can be then added to the induced drag calculated by VLM to get an overall drag build-up for the configuration.

The computational modelling is not enough. The aerodynamic analysis undertaken for the box-wing must be validated. Unfortunately large scale models have not yet been built or tested in wind-tunnels, meaning that validation must be based on non-empirical methods for the most part. The effect of wing stagger was investigated by Bagwill and Selberg (1996), who also confirmed earlier results that box-wing aircraft could be more aerodynamically efficient (with respect to the lift-to-drag ratio) than a conventional aircraft of the same span, depending on the gap ratio used. However their key result was the fact that box-wing aircraft with positive stagger are more efficient than aircraft with negative stagger (Bagwill & Selberg, 1996). Positively-staggered wings have the forward wing higher than the rear wing, and negatively-staggered wings are the opposite. However the study was conducted for only a single set of wings, under a certain flight condition, and few explanations are offered for the results.

The studies conducted by Mamla and Galinski (2009), Altman (2008) and Landolfo and Altman (2009) also consider the effects of gap and stagger, from the perspective of biplanes and UAVs in particular. The interesting findings from these studies (include theoretical analysis and some wind tunnel testing) is the importance of gap and how crucial it is to performance. Of course due to overall maximum size of UAV models under consideration here it is hard to scale the same results up to larger aircraft but the work definitely underlines the importance of considering the relationship between gap and aerodynamic performance from a parametric perspective.

Genco and Altman (2009) also consider the influence of stagger and find that positive stagger leads to better efficiency and performance but this influence was smaller as the gap increased the interaction between the wings diminished in turn. Definitely this parameter needs further investigation to verify the magnitude and reliability of this relationship for the box-wing configuration as opposed to the biplane analysed in these studies.

Also relevant here is the fact that a box-wing configuration usually consists of a swept forward wing and a swept back wing, which has implications for the induced drag calculation and thus the overall analysis. As Löbert (1980) states, the spanwise lift distribution for a forward-swept wing corresponds more closely to the optimum elliptical lift distribution required for aerodynamic efficiency, causing some interesting vortex shedding behaviour especially at higher angles of attack (Lombardi, 1993). McGeer's (1984) work on optimum wing design also bears out the implications of this, on monoplane aircraft. Of course some of the real experimental work on this topic does not completely bear out the theoretical implications, especially flight testing with the famous X-29A demonstrator (Hicks & Huckabone, 1991) which showed up to 20% reduction in induced drag compared to wind tunnel and theoretical estimates. Thus the contribution of this effect on the Prandtlplane aircraft has to be recognised and kept in mind when looking at the causes of the efficiencies gained.

One of the few studies that analysed the effect of the box-wing in a wind-tunnel looked at it from a different viewpoint by considering the efficiency increase when endplates are attached to a biplane (Ahmed & Archer, 2001). This configuration is for all intents and purposes aerodynamically identical to a box-wing, and hence the results are relevant for this purpose. The resulting improvement in drag polar found in these wind tunnel tests shows that the inhibition of wingtip vortices by attachment of endplates as theorised does actually take place and improve the aerodynamic efficiency of the wing. Of course as this study was comparing normal biplanes to biplanes with endplates (i.e. not conventional monoplane configurations) the actual numbers are less useful than the demonstration of the effect of endplates themselves. Another study considered the similar joined-wing configuration, looking at the effect of attaching them to bombs and missiles (Corneille, 1999), and found them to outperform conventional configurations as predicted by the theoretical analysis.

However many studies did compare the aerodynamic analysis of box-wing configurations using VLM to conventional configurations, using the same methodology to consider both kinds of aircraft, and ensuring that the conventional configurations were either the same or reasonably close in terms of aerodynamic characteristics to real-world aircraft (Frediani, et al., 2003), (Jemitola, et al., 2013), (Mamla & Galinksi, 2009). This at least ensured the methodology implemented was sound for the conventional designs and the box-wing results could hence be relied upon to be somewhat accurate, at least in terms of the accuracy required for the conceptual design estimates and analyses being conducted.

One final consideration that must be considered is the effect of the elliptical load distribution. While it is well established that the optimum aerodynamic lift distribution for the box-wing has the classical elliptical shape on the horizontal wings (Prandtl, 1924) (Frediani, 2005), this may well not be the case when considering a multidisciplinary approach that includes both aerodynamics and structures. Iglesias (2000) found that when considering structural span loading and aerodynamic performance of conventional aircraft together, an optimal loading that was more triangular (shifted more of the bending relief inwards towards the root of the wing) produced an overall reduction in wing weight and increase in induced drag. Together this lead to an overall reduction in the maximum weight of the aircraft, and hence more efficient performance (Iglesias, 2000). Similarly, for non-planar lifting surfaces it was found that the optimal aerostructural lift distribution tended away from the classic elliptical shape to one that was more triangular especially when considering raked wingtips or winglets (Jansen, et al., 2010). Conversely, high-fidelity multidisciplinary optimisation studies of subsonic transport aircraft found that weight and fuel savings from a optimally transversely loaded wing, which has more bending moment and root and is structurally hence more efficient, is not significant for typical transport aircraft when considering a typical cruise load case (Takahashi, 2012). For this study, the initial analysis will be done based on the classical elliptical load distribution as the validity of the alternative is not proven, but this is an important consideration for possible further studies and effect on results.

Stability and control of box-wing aircraft is an extremely complex investigation and design study on its own, and has been the focus of multiple research projects already (Andrews & Perez, 2014), (Voskuijl, et al., 2012), (Bosma, 2010). However for any design study focused on the box-wing, at least a partial look at this particular discipline is necessary even at the conceptual design stage so that it can be incorporated into the design process early. As pointed out in other studies (Schiktanz & Scholz, 2011), there exists a fundamental conflict between longitudinal stability and aerodynamic efficiency for box-wing aircraft. This arises due to the fact that one of the conditions for the most efficient aircraft aerodynamically in terms of the configuration is that the lift must be equally divided between the front and rear wings. However in most box-wing designs, the rear wing is often situated at the top of the vertical tailplane in order to ensure the maximum vertical separation is achieved. This then leads to a design where half the generated lift is at the very rear of the aircraft, presenting a challenge when it comes to ensuring the aircraft is stable and controllable.

The stability and controllability of an aircraft is defined by the envelope of movement of its centre-of-gravity (CG). The forward limit of this envelope is defined by controllability requirements, while the rearward limit is the neutral point, which is defined by stability requirements. For a stable and controllable aircraft, the neutral point must be behind the forward limit of the CG envelope. The pitching moment of the aircraft, that is the longitudinal moment around the CG, must be such that the coefficient of the pitching moment is greater than zero (Schiktanz & Scholz, 2011). In Fig 2-7, Wolkovitch (1986) shows the unique weight and balance considerations present for box-wing and joined-wing aircraft.

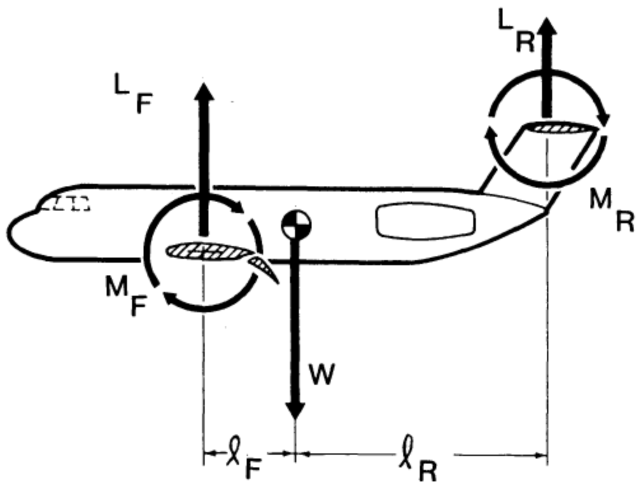


Figure 2-7 Box-wing aircraft lift generation (Wolkovitch, 1986)

This is especially problematic for the box-wing configuration due to the fact that moving half the lift to the rear wing and increasing the distance between the rear wing and front wing in terms of geometry means the CG shifts further backwards, leading to some configurations becoming unstable and potentially even uncontrollable (Frediani, 2005). There have been a few methods proposed as a solution to this problem, including the simplest, which is violating the condition of equal lift distribution on both wings. While this leads to a drag penalty and to hence to an overall decrease in the efficiency of the box-wing configuration compared to the optimum, this penalty may well be small enough to ensure that overall the box-wing is still the superior configuration for a given mission requirement. For example, for one particular mission, the imposition of stability requirements led to a 3.4% decrease in the overall span efficiency factor of the configuration (Schiktanz & Scholz, 2011). The problem is underlined for all designers working with this configuration however- how can this aircraft be made stable for the least possible drag penalty, including trim drag. A few other studies had also tackled this issue.

Another study using VLM for the aerodynamic and stability/control analysis of a box-wing configuration in comparison to a conventional configuration found similar results (Andrews & Perez, 2014), employing multidisciplinary optimisation that used a particle-swarm algorithm. Increasing the horizontal wing separation meant that that the CG had to be moved forward to ensure longitudinal stability could be maintained. This study considered a single mission with a range of geometric variables including sweep, dihedral and so forth, imposing a number of stability and performance constraints and optimized for minimum take-off weight. No structural analysis was undertaken. A statically stable aircraft configuration was produced, however there was no improvement found over the conventional configuration after the optimisation was undertaken (Andrews & Perez, 2014). The lack of considerations of other missions, as well as the fact that no structural analysis was undertaken means the actual analytical comparisons from this study are relatively unimportant, but the methodology and coupling of aerodynamic and stability analysis is critical and should be considered necessary by any design team working on the box-wing concept.

The flight-mechanics and propulsion of a box-wing medium-range box-wing airliner were analysed by another study which also considered the longitudinal stability problem, as well as more complex controllability issues (Voskuijl, et al., 2012). In this case an already designed box-wing model was analysed using a CFD tool and an in-house flight mechanics modelling environment. In this case, there was no design space analysed, simply one aircraft was thoroughly examined and a novel control system allocation was designed. This is a detailed design study that can only be undertaken once a particular concept has been chosen and its geometric parameters largely fixed for a certain set of mission requirements. The analysis found that the longitudinal stability of this model was acceptable given that there was a relatively small horizontal separation of the wings, and that more careful consideration was required for roll mode and the Dutch roll mode in terms of handling qualities (Voskuijl, et al., 2012). Another detailed control study of the box-wing configuration also used VLM to analyse the stability and control requirements for a medium-range box-wing aircraft and found that a control system using a daisy-chain allocation was the most superior arrangement for this configuration (Bosma, 2010). Again, this was a detailed design study, but what was of most importance was the methodology including the analysis of aerodynamic and stability characteristics using VLM.

The validity of VLM codes versus CFD codes for stability analysis for box-wing configurations was investigated by another study which considered high-lift systems (Iezzi, 2006), finding that VLM models proved less accurate when the fuselage was incorporated into the analysis but for planar-wings only analysis, they proved surprisingly accurate and similar to the CFD results for a fraction of the computational cost (Iezzi, 2006).

What becomes immediately clear from consideration of these studies is that conceptual design incorporating some basic stability criteria is paramount when analysing the box-wing planform. Right from the start, the stability requirements play a very large part in determining which geometric variables can be changed and which must be limited for even the most basic stability requirements. In this case, in contrast to conventional configurations, stability is not something that can be considered after the initial aerodynamic and structural design process takes place, but must be included side-by-side with them in the conceptual design stage. The drag penalty that must be taken into consideration, for example, for maintain longitudinal stability may well cancel out any aerodynamic efficiency gains for a particular configuration in a given set of mission requirements.

Countering this is the fact that it is clear that any deeper analysis of the stability and control of the box-win geometry requires a detailed design that is relatively constrained in terms of design and geometric variables. In this case it is clear that only a few very basic stability characteristics such as longitudinal pitching moment and hence the static longitudinal stability can be including in the preliminary multidisciplinary conceptual design process when considering the box-wing configuration.

The other outcome of importance is that similarly to the aerodynamic analysis, the stability analysis for box-wing aircraft is also generally conducted using either CFD or VLM techniques. The detailed design studies generally tend to utilise the CFD procedure, trading off the larger, more intensive computational efforts required, while the conceptual studies undertaken tend to prefer VLM analysis, accepting coarser-fidelity results from simpler models in order to cover a larger design space and more configurations. VLM is generally also considered suitable only for the analysis of basic stability considerations such as pitching moment calculations, which are of greater importance than a detailed control system design for example, during the conceptual design stage. Hence there is a synergy between the methodology used and the stage of the design process it is generally applied to.

Just as the aerodynamic and stability considerations of the box-wing configuration cannot be considered independently when design such an aircraft, the structural considerations of the design, especial of the unique unconventional wing planform, also cannot be considered separately to the rest of the design challenge. Indeed for these kinds of non-planar wing planforms such as the box-wing and the joined-wing, the aerodynamic and structural characteristics are even more intrinsically linked than for conventional planforms, meaning they must be considered simultaneously when designing and assessing the most efficient wing system for any given mission (Wolkovitch, 1986).

Hence the classical methods of weight estimation as available for conventional cantilever-winged aircraft (Roskam, 2005), (Torenbeek, 1976) and (Raymer, 2012) are not viable in the cases of box-wing aircraft. However wing-mass estimation is critical for the early conceptual design stage of an aircraft, and the traditional statistical methods no longer being applicable means an alternative method for the structural analysis must be found. Although these methods are still found in some studies (Schiktanz & Scholz, 2011), their fundamental flaw is that the structural loading and design of non-planar wing concepts is so widely different from the conventional (Wolkovitch, 1986) that these results cannot be considered valid for the box-wing at all.

It is clear that analysing the wing’s structural model and hence its weight is the most critical part of the structural analysis required for the box-wing because the fuselage of the aircraft is relatively similar to a conventional design. Unlike with a blended-wing-body aircraft, the standard tubular fuselage model is also used by the vast majority of the box-wing aircraft configurations, and these fuselages can of course be modelled using statistical methods relying on historical data. While some minor modifications might be required for changes such as strengthening the empennage and so forth, the bulk of the structural analysis is limited to the wing planform.

One approach outlined earlier (Jemitola, et al., 2013) considered modifying or adapting the statistical approach to be used by box-wing configurations, by analysing said configurations using finite-element analysis and then modifying the statistical coefficients present in a wing-mass estimation equation. However this approach has only a narrow range of applicability to those designs that fit the missions parameters used for the configuration used to modify the equation. That is to say, each time a new mission or family of designs needs to be analysed, the process to generate the mass coefficient must be redone. This prevents it from being a widely-applicable methodology used in the conceptual design stage for structural analysis and mass estimation. The key result here is that box-wing aircraft need not necessarily be heavier than their conventional counterparts, as the box of the two wings itself adds a structural efficiency to the overall wing system, meaning savings can be made enough to bring the weight down to something similar to a conventional cantilever wing.

Another analysis utilised simple, low-fidelity methods for both aerodynamic analysis and structural analysis with a particle swarm optimisation routine to consider the optimal non-planar lifting surfaces (Jansen, et al., 2010). Unfortunately, even though the panel method potential flow-based aerodynamic solver is adequate, the equivalent beam model structural solver does not capture the full range of behaviour for the box-wing structure as outlined above in section 2.2. The result here that the box-wing is only the optimum when induced drag is considered (and without the effect of viscous drag and wing weight) hence is somewhat suspect. Furthermore, the mission being considered for optimisation here is a Boeing 737 and its associated wing, where it is possible that for alternative missions, the box-wing will present the most optimal solution including the consideration of viscous drag and structural analysis (Jansen, et al., 2010). This study does underline the necessity of capturing the behaviour of not just the aerodynamic performance and induced drag, but also of considering the zero-lift drag and the wing structure in the same conceptual design study in order ensure that a fair comparison is being conducted with regards to the box-wing and the conventional planform.

A multifidelity modelling approach to the box-wing configuration is considered in another study, which seeks to build a model initially using simple beam theory, then transition to thin-walled beam cross-sectional analysis before finally the third level of optimisation used is a finite-element analysis model (Bindolino, et al., 2010). The results for a conventional aircraft were compared to real-world data and found to be in relatively close agreement, and a box-wing analysis was also carried out using this same methodology. The model is shown in Fig. 2-8.

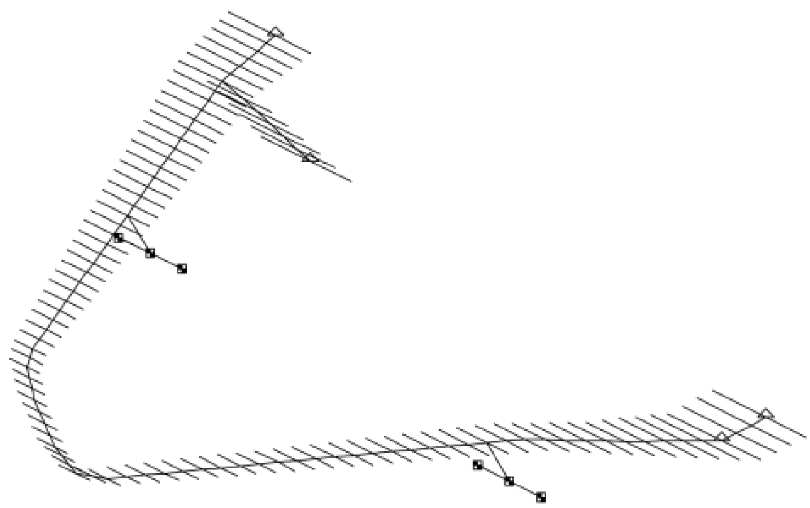


Figure 2-8 Box-wing first level structural mesh (Bindolino et al, 2010)

However, although this method worked well for conventional aircraft, it did fail to capture the proper behaviour of the box-wing structure until the final FE model was implemented. In this case the use of multi-level structural optimisation was relatively unsuccessful as the lower-level structural models did not accurately analyse the unique stiffness and bending behaviour of the box-wing model. The study hence actually underlines the importance of using FE analysis as early as possible in structural modelling of the box-wing, as its unique properties and behaviour in structural terms mean that coarser, lower-fidelity models will not be very useful in estimating the required masses.

There are of course a number of studies that consider the structural optimisation of non-planar wing concepts using high-fidelity FE models, but the vast majority of them focus on detailed design and the optimisation of a narrow range of geometries for best results inside a small design space (Rasmussen, et al., 2009), but in the conceptual design stage, automation and efficiency of such a modelling process is paramount so a large number of different designs can be analysed, especially if the design team considering the box-wing is faced with multiple missions and sets of requirements.

A toolchain that is based on extended physics-based wing mass estimation, taking into account aerodynamic loads, fuel, primary and secondary structures and implementing a sizing algorithm (Dorbath, et al., 2014) is more suited to the analysing the box-wing. This toolchain uses a common parametrisation language for aircraft developed at the German Aerospace Centre (DLR) to automate large parts of the modelling and analysis process, meaning that a higher level of structural analysis can be done with less computational time and effort.

This data is then used by WingMASS, the toolchain, which incorporates a central model generator to generate the requisite model and the geometry. This generator saves computational time and ensures the fit of all parts of the geometry before any analysis takes place. After the model has been generated, the core of the toolchain iteratively loops between the two loaded models and the sizing algorithm, which uses the commercial FEA software ANSYS for the structural calculations and VLM for recalculating aerodynamic loads within the loop (Dorbath, et al., 2014). Validated against real-world aircraft such as the Airbus A320 and A340, the toolchain has been found to similar to within a few percent compared to the actual wing weights for those aircraft.

This tool was further tested with unconventional designs, including the box-wing and the blended-wing-body, and showed results that were in line with expected values for those wing structures (Dorbath, et al., 2014). This kind of automated tool is best suited for use in analysing the structure of the box-wing, especially when considering a large design space during the conceptual design stage. The combination of the automation with the high-fidelity structural modelling ensure that relatively reliable wing weight estimates can be arrived at for a number of different configurations in terms of geometry. Furthermore the integration of the aerodynamic and structural sizing in the same sizing loop integrates two crucial disciplines of aircraft design that must remain coupled when designing box-wing aircraft.

The box-wing also presents a challenge in terms of a number of other disciplines such as propulsion, aeroelasticity, ground-handling, manufacturing and maintenance. While not all of these disciplines can necessarily be integrated into the conceptual design stage for any particular box-wing configuration or mission scenario, they should be kept in mind at least in broad terms as having an impact on the configuration and how they might impact on it moving into the detailed design stage.

Flutter is a very challenging issue for the box-wing concept, given the preponderance of long, narrow wings which are then not necessarily as stable as conventional cantilever wings, especially given the long, vertical wingtip that joins the front and rear wing which can act as destabilising element. Unfortunately flutter analysis is an extremely complicated and computationally-intensive task, as shown by one study which conducted flutter optimisation for a particular box-wing configuration already at the detailed design stage, which found it necessary to add significant skin thickness to dampen the flutter (Divoux & Frediani, 2012). This study also modelled the possibility of dampening flutter using tip tanks, but did not have a conclusive answer as to whether this was a realistic solution or not. In the main, this underlines the fact that at the conceptual design stage itself, designs that are prone to flutter should be avoided as much as possible, but analytical solutions to the problem of flutter are not possible till detailed design and analysis is being done on a particular configuration.

Propulsion and engine placement in particular are also concern for the box-wing configuration. The need to maximise the vertical gap between the two wings means that lower wing is as low on the fuselage as possible, and as forward as possible. This can constrain engine placement underneath the wing as per conventional aircraft design because of ground clearance and CG issues. Alternative placement has been explored in some design studies including at the rear of the fuselage, in between twin vertical tailplanes, underneath the rear wing or even in an over-the-wing nacelle configuration (Frediani, et al., 2012). The over-the-wing nacelle configuration alleviates those ground clearance concerns, for engines placed on the front wing but comes with its own additional issues regarding disrupted airflow and lift generation (Hill, et al., 2009). Ultimately, the placement at the rear of the fuselage, though it has its own issues regarding noise, vibration and structural loads on the fuselage, is likely the best option (Schiktanz & Scholz, 2011).

The issue of ground handling and cargo loading is also a problem, with standard loaders unable to be used for some geometric configurations due to fear of striking the wings if standard cargo loaders were used. An innovative solution was proposed in one case of a cargo door which split in two and had a sweep angle built in (Fielding, et al., 2010). High wing maintenance and airport interface issues were also noted by this study.

Essentially, while these design concerns are not necessarily all pertinent at the design stage issues, or can be confronted with coarse analysis at that fidelity level, they do all pose a challenge that must be eventually overcome. Sensible design policies and decisions that are undertaken at the conceptual design stage can mitigate or even solve some of these issues, and hence these issues must be kept in mind throughout that stage of the process while other disciplines are of a more primary concern.

2.4.Mission Requirements

The box-wing configuration presents a unique challenge and opportunity in terms of its characteristics, and to capitalise on these, it must be allied to the most suitable mission.. The primary consideration with the box-wing design is that it reduces induced drag, which is the component of overall drag of the aircraft generated by lift. This is due to the closed-wing system preventing the formation of wingtip vortices which are the largest source of lift-induced drag, by keeping the flow attached to the vertical wingtips that join the two horizontal wings, as explained in greater depth in section 2.2. For commercial aircraft, the induced drag is most dominant when the aircraft is in its take-off, climb, descent and landing phases. When it is cruising, the dominant component of drag is generally the zero-lift drag generated by the overall airframe as shown in Fig 2-9, which includes the friction drag from the surface of the aircraft, the profile drag from the profile of the aircraft headed into the free-stream and the interference drag from interference effects of the aircraft's design (Raymer, 2012). For box-wing aircraft, this component of the drag is relatively high (Frediani, 2005). Hence for the box-wing there is a pay-off between reducing the induced drag and increasing the zero-lift drag, meaning that designers that want the best drag performance out of the aircraft have to ensure that the requirements suit the aircraft's strengths and weaknesses.

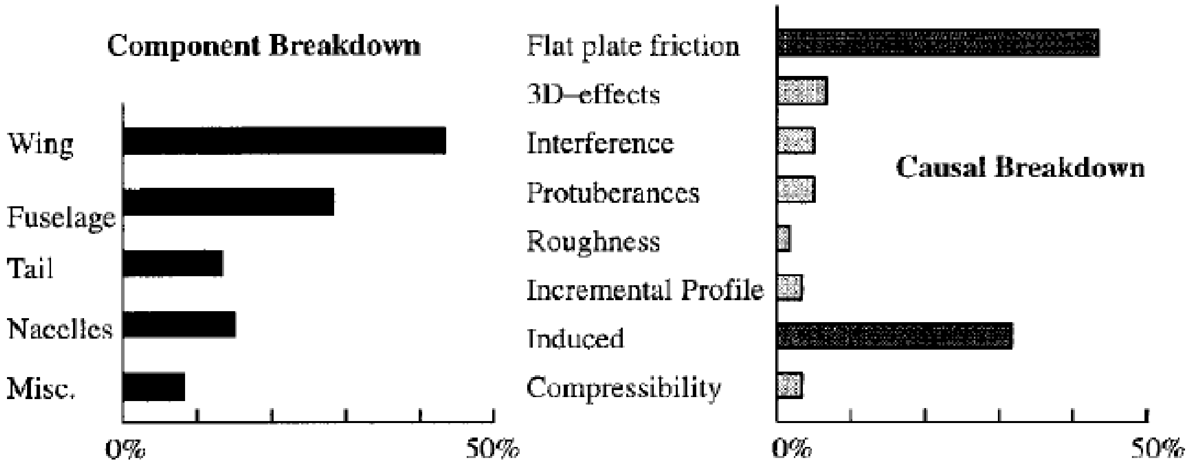


Figure 2-9 Drag breakdown by component for a typical jet transport (Roskam & Lan, 1997)

Hence, logically, the box-wing is best suited to missions where the cruise phase of the flight is relatively short, and the other phases of the mission are relatively long, meaning reducing the induced drag has a larger overall benefit on the drag reduction for the whole mission. This becomes clear when considering the Lockheed Martin box-wing design discussed earlier in section 2.2 of this chapter, where the longer-range, larger aircraft mission requirements lead to a box-wing that does not that have a reduction in fuel burn over the conventional for that kind of mission of 8000 nautical miles (Martin, 2012).

This means short-ranged, city-hopper missions of no more than 2000 nautical miles are ones the best suited to the box-wing configuration's unique characteristics. There is also a paucity of information in the literature regarding the box-wing configuration and its application to these missions- the vast majority of design studies that exist for the box-wing are either ones for very large aircraft that are intended to fly long-distance missions, or the medium-range aircraft flying at least 3000 Nm that are capable of serving many roles but are not optimised for them very well. The few that do consider them find them suited for the short-range role (Jansen & Perez, 2010).

However the choice of range is not the only parameter to be considered when focusing on mission requirements for the box-wing, especially the city-hopper use case. Other parameters that are commonly used to define performance requirements include cruise Mach number, the payload and cruise altitude, and rather than simply using the commonly-accepted values that are defined by current aircraft, it is interesting to consider some of the research being done in these areas to consider what might be more suitable for a box-wing and the environmental challenges it is designed to meet overall.

Fillipone (2007) analysed the benefits of a lower cruise Mach number, finding that there is a saving of up to 1.8% available per 1000 Nm segment of cruise for lowering the Mach number by just 0.02 or 0.03. The slightly longer flight time is barely perceptible given operational considerations such as loiter over the landing airport, being less than three minutes per 1000 Nm flight segment. The fuel saving is actually compounded due to the reduction in take-off weight from carrying less fuel and the lower consumption in each segment. Though this analysis was conducted for a long-range aircraft, the application and savings for a city-hopper scenario where a box-wing would operate are clear.

Similarly, another study on the impact of changing cruise altitude (Koch, et al., 2011) found that lowering the cruise altitude could yield significant reductions in cost and environmental impact from the same flight. Though again the mission considered here was one for a larger aircraft with a longer range, the significant benefits derived and their applications to the shorter-range aircraft (which spend a much shorter portion of their overall flight in cruise, and hence benefit more from a lower cruise altitude) are absolutely clear. Further studies into this particular performance requirement often imposed on new aircraft have shown that these reductions are possible without significant increase in travel time (Williams, et al., 2002) and must be considered as a vital step in reducing the environmental impact from air travel (Reynolds, et al., 2010).

Hence the use case for a box-wing in a short-range mission scenario, with mission parameters differing from currently-flying aircraft is clear. It is most likely that it is in this scenario that the box-wing will be the most advantageous configuration for designers, but there is a distinct gap in the literature that would help verify that possibility or eliminate it.

2.5.Gap Analysis

While the box-wing concept seems to offer a number of significant advantages over current design configurations, those are yet to be really quantified for certain mission scenarios, and the multidisciplinary design methodology required for this novel configuration to be analysed at the conceptual design stage has not been fully established. The establishment of a toolchain and reliable validation would provide a large help for any design teams considering the concept in the future. Conceptual design for all unconventional aircraft planforms is a relatively uncharted field, and the lack of reliable methods and historical and statistical data which are keystones to conventional aircraft design has long proved a large hurdle for the unconventional concepts to become more accepted.

Furthermore, much of the research has been at the detailed design stage with high-fidelity modelling, meaning that the broader design space for certain missions for the box-wing has not been fully explored and published in literature, contributing to the paucity of knowledge in the field about this type of aircraft. Even when it has been done, it sometimes has been done employing methodology that is outdated or erroneous and can be improved, and hence the results made more reliable. The chaining of multiple disciplines such as aerodynamics, stability and structures is of paramount importance during the conceptual design stage of this configuration, due to the unique challenges it poses, and the coupling of all three elements has not yet been attempted by any of the design studies focused on a larger design space for certain missions.

These relatively few design studies do establish that the box-wing concept does hold great promise in terms of the future environmental and cost challenges that face the civil aviation industry, however the correct niche for the box-wing configuration is yet to be found in terms of maximising its advantages and minimising its disadvantages. Finding this mission scenario and quantifying exactly how much of an advantage the box-wing offers over conventional aircraft in those scenarios is the first critical step to truly critically assessing the overall impact of the concept and whether it is promising enough to continue to pursue.

Unfortunately, most design studies and investigations of this concept so far have focused on mission scenarios for the box-wing which utilise it for long or medium-range missions, ignoring the fact that its strengths and flaws actually make it more likely to be suited for a short-range design case, as is also found by Jansen and Perez (2010). Its clear strength of minimising lift-induced drag comes with a price in terms of increased zero-lift drag, implying that it is best used in missions where the former is as dominant as the latter, meaning the short-range missions where the least time in spent in the cruise condition and the reduction in induced drag can lead to the greatest reduction in fuel burn possible. That sets the payload and mission range scenarios. Allying that with small changes to design parameters, in terms of Mach number and cruise altitude, that are the standard for current conventional aircraft, a gap of need appears in terms of design studies done with box-wing aircraft where new research is required.

Thus it can be seen that there is a need for an exploration into the box-wing configuration at the conceptual design stage from a multidisciplinary point of view, in order to establish a baseline understanding of it, especially one sized to meet the short-range passenger jet market where the advantages of this configuration are maximised. This kind of study needs to be relatively computationally quick in order to cover a large design space and vary a number of parameters in order to be helpful to future designers. It will be largely responsible for identifying the most promising areas of future research for the box-wing design and how it should be further pursued in research in terms of detailed design studies incorporating higher-fidelity methods. Establishing this design space and direction for future research, as well as providing the preliminary analysis into total improvements a box-wing configuration can offer will absolutely fill some of the vital gaps in the research of this type of aircraft.

2.6. Key Research Questions

There are specific questions that arise from the gap analysis that will be the focus of this research, centred on the box-wing and the missions it is best suited for:

- What is the best framework and associated processes for conducting a multidisciplinary design analysis of a box-wing aircraft configuration for a given mission scenario?
- What are the effects of geometric parameters of the box-wing configuration and the interaction of aerodynamic and structural characteristics, on overall fuel burn?
- How do mission requirements influence a box-wing configuration design of a short-range aircraft?
- What improvement in fuel burn can be achieved with the box-wing configuration over a conventional aircraft for a given mission?

Answering all of these questions will serve to extend the knowledge about the box-wing, and present future designers and researchers with valuable information that can be built on for further endeavours in the field.

3. Methodology: Theory and Tools

3.1. Theory

3.1.1. Aerodynamics - Vortex-Lattice Method

The linear vortex lattice method (VLM) for predicting aerodynamic flow solutions provides a computationally efficient and reasonably accurate solution to wing models and thus is especially helpful for parametric exploration. The Navier-Stokes equations are simplified by assuming steady, attached, incompressible, non-rotational and inviscid flow.

Hence, linear vortex-lattice methods provide a numerical analysis by calculating three-dimensional forces and coefficient for a given wing geometry. The Biot-Savart law describes the effect of a small section ($\overrightarrow{\mathbf{dl}}$) of a vortex filament on the velocity ($\overrightarrow{\mathbf{dV}}$) at a point in the flow field.

$$\overrightarrow{\mathbf{dV}} = \frac{\boldsymbol{\Gamma}}{\mathbf{4\pi}} \frac{\overrightarrow{\mathbf{dl}} \times \vec{\mathbf{r}}}{|\vec{\mathbf{r}}^{\mathbf{3}}|} \tag{5}$$

Here, $\boldsymbol{\Gamma}$refers to the vortex strength and $\vec{\mathbf{r}}$ is the vector from $\overrightarrow{\mathbf{dl}}$ to a point downfield. This can then be further extended for wing aerodynamics as developed by Prandtl, by placing a bound vortex filament of a given strength from tip to tip of a finite wing (Bertin & Smith, 1998). According to Kutta-Joukowkski theorem, this leads to a lift force of

$$\mathbf{L} = \boldsymbol{\rho}_{\infty}\mathbf{V}_{\infty}\boldsymbol{\Gamma} \tag{6}$$

However, as this vortex cannot end at the tip, it is continued as a free vortex filament at the wingtips downstream to infinity. The free filaments induce a downwards velocity at the tips and their shape means they are called horseshoe vortices. A single such horseshoe vortex is not able to model an entire wing geometry hence the wing is divided into quadrilateral panels, the size of which can be specified for greater or lesser fidelity. On each of these panels, a horseshoe vortex is imposed, as shown in Figure 3-2, and then the Biot-Savart Law (along with the Kutta-Joukowski Theorem) as per equations 5 and 6, can be utilised to calculated the induced velocities from each of these vortices at the control points, and hence a set of equations for the strengths are arrived at when the all the points on the wing are added together (Anderson, 2001).

The horseshoe vortices imposed on each panel are placed along the quarter-chord line of the panel, and this combination of vortices at each panel (with the whole wing being comprised of a lattice structure of these panels as shown in figure 3-2) indicates why the method is known as vortex-lattice method. The control point of each panel is centred spanwise on the three-quarter-chord line, midway between the trailing vortex legs, and is used to calculate the influence of the imposed vortices on each other (Bertin & Smith, 1998). Figs. 3-1 illustrates the region of analysis with VLM.

The pressure differential and circulation between the upper and lower wing surfaces are connected by the strengths of the vortices, and when the pressure differential is integrated the forces on the wing are found (Bertin & Smith, 1998). Bertin and Smith's (1998) work contains a full derivation of vortex-lattice theory and can be referred to for a greater understanding of the method.

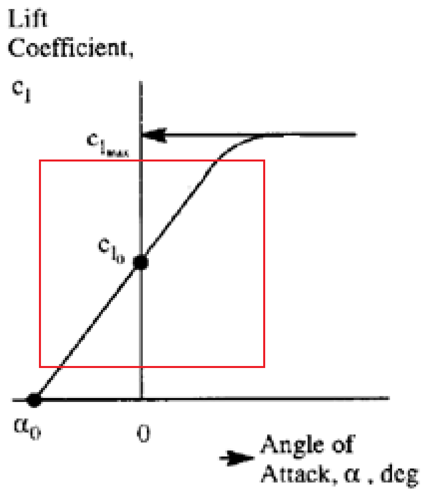


Figure 3-1 Linear region for analysis with VLM (Roskam & Lan, 1997)

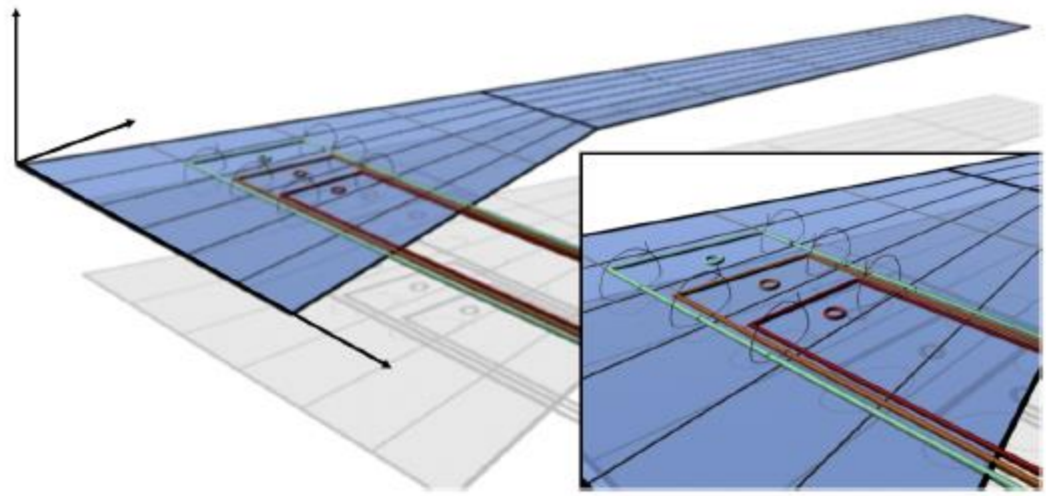


Figure 3-2 Vortex-lattice analysis arrangement (Paiva, 2005)

Research on analysis of non-planar wings and wing models using linear VLM has found that it is a reliable predictor of lift, induced drag, and some quasi-steady stability derivatives (Kalman et al, 1970). Currently, there are several linear VLM codes that incorporate the ability to analyse non-planar lifting surfaces and combinations of lifting surfaces and hence are suitable for the geometric parametric variation aspect of this investigation. Compressible flow is an issue with VLM, however there are some ways to correct for those challenges, including the Prandtl-Glauert correction factor which is what is implemented for the analysis during this investigation. It does mean that Mach numbers over 0.8 cannot be analysed with any reliability due to errors creeping into the results from shocks and flows that cannot be modelled by VLM.

3.1.2. Structures - Beam Model

Initially an approach that structurally modelled the wing using simple beam bending theory was trialled, however initial experimentation with this method revealed that it was not suitable for the box-wing. The complex bending and twisting behaviour of the box-wing could not even be somewhat accurately captured by this method, and without that the wing weight estimation and the structural analysis of the configuration could not be undertaken with any certainty. This then meant that an approach centred around Finite Element Analysis was absolutely critical.

3.1.3. Structures - Finite Element Analysis

Finite Element Analysis or Method (FEA or FEM) is a mathematical numerical analysis technique that relies on discrete approximations to find solutions to differential equations. In engineering, this is an applied tool that is used mostly for structural analysis in a wide variety of fields such as aerospace, mechanical, manufacturing and automotive engineering.

In aircraft design, it has been long used for analysis and design of aircraft structures and components, from large structures such as the whole wing or fuselage to very small structures such as individual rivets or lugs. It is common to now use FEA in the detailed design section of any aircraft design project to calculate the stresses on the aircraft structure from the loads, and use it to size the various structural components.

The underlying theory of FEM is to break up the analysis of the structure into several discrete areas (the elements) and on each element the analysis can be undertaken using simple interpolation based approaches. Each element tends to consist of several points called nodes, which are used to connect the elements and constrain them, as well as apply the necessary loads for the analysis being undertaken (Cook, et al., 2001).

These nodes can then move and rotate in response to the loads placed upon them in a manner corresponding to their degrees of freedom. The displacement and rotation of these nodes leads to a linear system of equations that can be solved for the degrees of freedom being analysed while the stress and strain values are then found during post-processing from the overall displacement and rotation of the entire structure that has been analysed (Cook, et al., 2001).

$$\bar{\bar{\mathbf{K}}}\vec{\mathbf{d}} = \vec{\mathbf{F}} \tag{7}$$

For a linear, static analysis equation 3 represents linear equations used to solve the problem. Here, $\vec{\mathbf{d}}$ represents the vector of all the degrees of freedom, $\vec{\mathbf{F}}$ the forces acting on the nodes in the direction of the degrees of freedom and $\overline{\overline{\mathbf{K}}}$ is the stiffness matrix that relates the two. The derivation of the stiffness matrix depends on the structure and how it is constrained, and the energy contained in the system (Cook, et al., 2001). Shell (two-dimensional) elements are 4-node structural elements with 6 degrees of freedom at each node, which is used for both the non-linear and linear analysis present in this study (Dorbath, 2014).

A number of commercial software packages exist that undertake the computation of these kinds of models, such as ANSYS, PATRAN/NASTRAN and HyperMesh. These software packages are tested and validated, and used widely as industry standard by aerospace engineers to undertake the requisite structural design analysis.

3.2. Tools and Software

3.2.1. Athena Vortex Lattice (AVL)

Athena Vortex Lattice (AVL) is a freeware, FORTRAN-based linear VLM solver written first by Drela and Youngren at MIT that is widely used for preliminary aerodynamic analysis (Drela & Youngren, 2006). A modified batch version of this software was used for this project, and rigorously tested and found to work with a variety of different inputs and conditions, and only served to speed up and add flexibility to the pre- and post-processing of AVL results.

AVL has also has limitations, which constrains its use to a certain set of modelling conditions. It can only be used for subsonic flows, i.e. Mach numbers less than 0.8. Similarly, the program does not take into account zero-lift drag coefficient (${C_D}_o$), so that must be estimated separately. Analysis should be at low angles of attack as AVL only models attached flow and tends to over-predict aerodynamic values at higher angles of attack. Drela and Young (2006) mentioned that AVL is meant for thin airfoils at small angles of attack and sideslip, but interpretation of the value of 'small' is left up the user- as a linear code, AVL functions accurately within the linear range of the $C_L - \alpha$ curve (up to approximately 15^o depending on the airfoil).

However, despite these limitations AVL has been used in a number of different design studies and experiments. The work of Genco and Altman (2009) is one example where AVL aerodynamic values were compared with data from wind tunnel testing for non-planar wing configurations and found AVL's theoretical calculations accurate, especially at lower angles of attack. Melin (2000) compared AVL data with another computational VLM and existing data to find good correlations especially for simple wing geometries. Iezzi's (2006) work on Prandtlplanes with AVL shows that it is useful for predicting lift coefficient and effect of working with different angles of attack compared to experimental data collected. Mamla and Galinski (2009) also used AVL for their analysis of joined-wing aircraft and found reasonable results, and Garcia and Becker (2008) also found reasonable correlation between AVL and real world values for UAV stability and control, specifically pitching moment, which incorporate aerodynamic qualities along with other values, albeit at small magnitudes due to the size of the aircraft tested. Landolfo and Altman (2009), and Altman (2008) also found AVL a useful tool for UAV conceptual design and analysis with non-planar wing configurations as it provided reasonably accurate estimates of the values required. An error estimation of the toolchain is presented in section 4.6.

In this case, it was necessary to link AVL to MATLAB in order to ensure the wing lift distribution was being optimised. A batch version of AVL was linked with a MATLAB tool that was written to vary the twist along the wingspan in order to ensure that the lift distribution along the span of the wing was elliptical. The wing was divided up into eight sections along its span, and each of those sections had a separate twist angle which could be specified individually. Of course, it was necessary to maintain realistic geometric consistency of the wing, and hence the tool was limited to only allow a maximum change in twist of one degree between sections of the wing next to each other. This elliptical lift distribution is especially important for box-wing configurations, as the theory specifically states that maximum drag reduction and hence aerodynamic efficiency can only be achieved when there is equal and elliptical lift distribution on both horizontal wings. This change in the wing geometry was taken into account and implemented when the wing was analysed and sized structurally to ensure consistency of results. The twist optimisation is necessary as the other geometric parameters such as wing area and aspect ratio are either going to be fixed for comparison purposes or be part of the parametric sweep which will necessarily cover values which aren’t optimal.

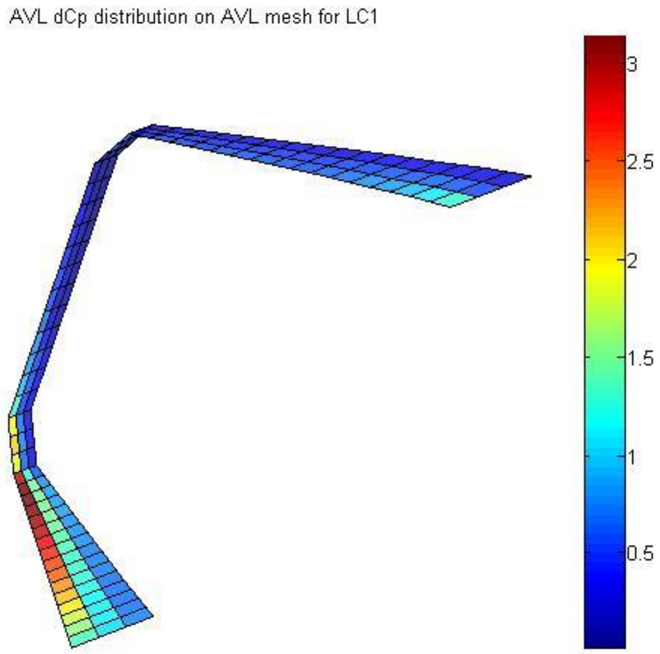
The aerodynamic analysis with AVL was conducted for the cruise condition only, which is also discussed further in Section 4.3. The output of the aerodynamic analysis and optimisation, specifically the lift and induced drag, will be necessary for the performance analysis. Furthermore the aerodynamic loads will be transferred over to the structural analysis tool and serve as the input loads for that link in the toolchain for the design.

3.2.2. WingMASS

As described, FEA has been used in engineering analysis for structural design for many, many years and is a key part of doing any kind of design study that incorporates structural design analysis and optimisation. In order to aid the aircraft designer and analyse a large range of conventional and unconventional wing configurations in a relatively computationally efficient manner, a new tool was developed at the DLR Institute for Air Transportation Systems called the Finite Element Wing Structure (WingMASS) (Dorbath, 2014) in order to improve the structural design and weight estimation aspect of wing design in the conceptual and preliminary design stage of the process and incorporate an FEA approach into those stages in order to provide a more accurate structural design of the wing planform (Dorbath, et al., 2014).

The strength of the WingMASS toolchain is that it allows for relatively large and complex models to be built up and analysed with reasonable speed and efficiency by using the Common Parametric Aircraft Configuration Scheme (CPACS) developed at DLR, which is an XML-based language for several aircraft design tools from various disciplines (including WingMASS) that allows designers to rapidly generate different models. Furthermore several engineering rules are implemented into the toolchain, minimising the amount of user input required and allowing for a higher level of automation in terms of optimisation and analysis (Dorbath, 2014). The CPACS file is where all the parameters (aircraft geometry, mission, material properties and so forth) are stored, and are used to initialise each analysis run.

The first loop model is the undeformed wing and the initial aerodynamic loads as generated from the aerodynamic analysis derived from the performance requirements. This is sized and iterated till the weight converges. The deflections calculated are then fed back into the loads model and loads are re-calculated and the wing is once more subjected to the sizing and iteration loop. Once the second outer loop has converged, the analysis is considered complete and the outputs are generated (Dorbath, et al., 2014) in order to determine the structural weight of the wing. Fig. 3-3 shows the pressure differential distribution for the wing's load case for one particular configuration and load case, and how it deforms with each iteration and the analysis then being undertaken with the progressively more deformed wing shape. This demonstrates how the analysis and the sizing is responsive and reactive to the load cases and the flight conditions that are imposed on the wing, and how those are taken into the account when the wing sizing is done via this tool.



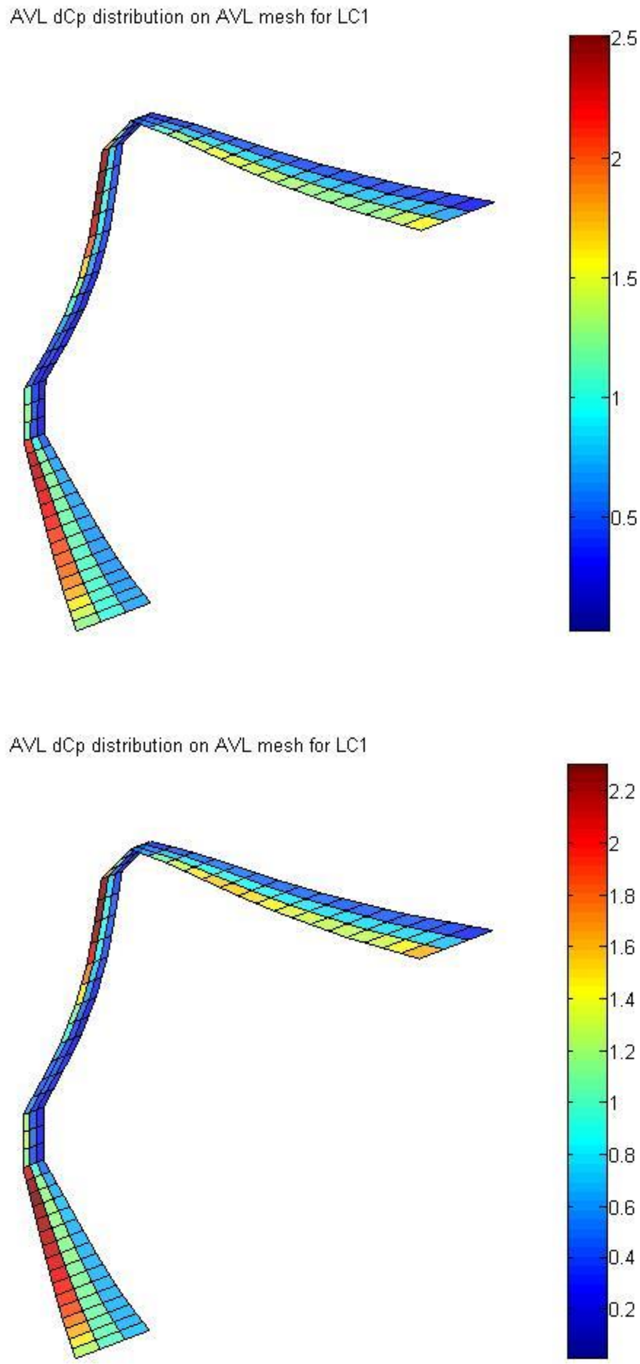


Figure 3-3 Wing model deformation with iterations of analysis loop showing aerodynamic loading via differential pressure distribution

A basic structural model is generated using quad elements for the basic structural members of the wings, the skin, the spars and the ribs. They are all modelled as shell elements, and where composite materials are used, multilayer shell elements are created. Stringers are then modelled as a smeared skin, with the equivalent stiffness and materials properties of an explicit stringer model. The spar caps are modelled as beam elements with rectangular cross-sections (Dorbath, 2014).

The structural sizing and analysis is done by the Sizing Robot (S_BOT+) element of the WingMASS toolchain, which is implemented in ANSYS Parametric Design Language (APDL). The sizing is done via an iterative sizing loop that initially considers all the loadcases implemented in the CPACS file, sizes accordingly, after which the new material thicknesses are applied to the model and the loop begins again and continues till convergence of material thickness and hence mass.

S_BOT+ uses a fully-stressed design principle with regards to thickness calculations, meaning the thickness of each element is scaled to the ratio of the allowed stress to the actual stress using material limits. The load cases undertaken are mostly for ultimate loads, while fatigue load cases are considered by reducing the material's limits. Von Mises stress criterion is used for shells with isotropic materials such as metals, while composites can be analysed under a range of criteria available to the user such as von Puck or Tsai-Wu. Beam elements are sized according to either Von Mises or the maximum stress criterion (Dorbath, et al., 2014). The fully-stressed criterion is shown in equation 4. This usually very close to the optimal mass design and leads to good estimates during the preliminary design process (Dorbath, 2014).

$$\frac{\boldsymbol{\sigma}_{\mathbf{actual}}}{\boldsymbol{\sigma}_{\mathbf{crit}}} = \mathbf{1} \tag{8}$$

As the load inside the structure is dependent on the thickness values of the structure itself, an iterative process is used with the thickness of the next iteration computed according to equation 9 per Dorbath (2014).

$$\mathbf{t}_{\mathbf{i+1}} = \mathbf{t}_{\mathbf{i}}\left(\left(\frac{\boldsymbol{\sigma}_{\mathbf{actual}}}{\boldsymbol{\sigma}_{\mathbf{crit}}} - \mathbf{1}\right).\mathbf{k}_{\mathbf{red}} + \mathbf{1}\right) \tag{9}$$

Here $\mathbf{k_{red}}$ is a reduction factor which is used to regulate the convergence behaviour. For this investigation, it will be kept at 1, meaning standard fully-stressed criteria will be applied though this value can be tweaked for faster or slower convergence (and resulting changes in convergence behaviour).

Furthermore, a stability analysis is undertaken for the beam and shell elements, taking into account a critical buckling stress which is compared to the actual stress, with this ratio then being used to compute new thickness values. The critical stress for stability analysis not based on material values, and is instead computed using equation 10 (Dorbath, 2014).

$$\boldsymbol{\sigma}_{\mathbf{crit}} = \frac{\boldsymbol{\pi}^2\mathbf{kE}}{\mathbf{12(1-\boldsymbol{\upsilon}^2)}}\left(\frac{\mathbf{t}}{\mathbf{b}}\right)^2 \qquad \textbf{(10)}$$

Here $\mathbf{k}$ is the buckling coefficient, $\mathbf{E}$ is the Young's Modulus, $\boldsymbol{\upsilon}$ is the Poisson's ratio, $\mathbf{t}$ is the sheet thickness and $\mathbf{b}$ is the loaded edge of the plate. Internal computations in the model generator account for both the shear and compression loads, combining both into a final ratio which is used to calculate the new thickness as the buckling modes are not independent from each other (Dorbath, 2014).

For sizing the most critical criteria is always chosen out of all the load cases, for safety's sake. Structural sizing enforces that no buckling is to take place, and hence post-buckling is not a consideration for the analysis. The smeared stringer layer, on the other hand, is sized by stability criteria and not by fully-stressed criteria, with the shell buckling determining the stringer pitch, and other properties via the respective Euler equations or via Bruhn's handbook methods (Bruhn, 1973). Due to the smeared representation, the stringer parameters such as height, width and so forth are not explicitly present in the FE model, but defined by WingMASS as properties of the buckling areas and are used to compute the thickness and equivalent material properties of the smeared layer (Dorbath, et al., 2014).

Lastly, there is another tool within the WingMASS toolchain that deals with the secondary loads present in the wing structure, the Finite Elements Secondary Loads (ESEL) tool. This deals with the likes of the fuel loads, the landing gear loads and the engine loads. Due to the simplification necessary for the performance of the analysis in this study, the main concern out of these is the fuel loads. Fuel tanks are present in the model between the upper and lower skins and the ribs and spars of the model generated (users can define them more exactly, of course), and the CPACS load definition delivers the fill level of the tanks and rotations and acceleration of the aircraft. During the WingMASS analysis process, the ESEL tool computes the location of the fuel and the static pressure and loads from the fuel elements in the model. If the wing is deformed from a previous analysis, the structural mesh is also modified to take that into account. Hence the change in the fuel load to wing bending is taken into account during the overall analysis (Dorbath, 2014).

WingMASS was validated against real-world aircraft, specifically the Airbus A320 and A340 and against other weight estimation methods. While two aircraft is not a large sample size, the weight estimates delivered by a detailed design and its optimisation were promising (-0.2% for the A320 and 1.1% for the A340), and spoke to the validity and robustness of the methodology employed (Dorbath, 2014). It was also used to model unconventional configurations such as the blended-wing body and found to robustly model such configurations.

This is extremely useful and powerful for designers in the early stages of the conceptual or preliminary design process. While the toolchain can of course incorporate a more detailed and thorough design, a stripped-back version is perfect for analysis of unconventional wing configurations, especially the potentially troublesome weight estimation and structural analysis portion which forms a key part of the challenge in understanding the advantages and disadvantages of the box-wing configuration in relation to its conventional counterpart. Utilising WingMASS to undertake this kind of analysis and deliver the appropriate weight estimations in collaboration with the appropriate experts at DLR was the straightforward choice when considering the structural part of the process for this design analysis and research.

3.3. Statistical and Empirical Methods

For the initial design of the conventional aircraft for a given set of mission requirements, a large number of methodologies, historical data and guidelines exist in terms of designing large passenger aircraft of the conventional configuration that could be drawn upon as resourced during this initial part of the process (Raymer, 2012) (Roskam, 2005) etc. These could all be drawn upon and combined where appropriate to initially size the aircraft for the given performance and mission requirements, and estimate the weight and performance of the design.

3.3.1. Weight

The mass fractions can be estimated first, according to the chosen mission criteria which then determine the payload masses. The payload and fuel-burn estimate will allow the structural masses of the various components of the aircraft to be estimated, such as the fuselage and tailplane. Such a weight estimation method is presented for standard aircraft types based on statistical and historical data by Roskam (2005).

The take-off mass of the aircraft consists of the operational empty mass of the aircraft, the fuel mass and the mass of the payload:

$$\mathbf{M_{TO}} = \mathbf{M_{OE}} + \mathbf{M_F} + \mathbf{M_P} \tag{11}$$

The operational empty mass of the aircraft is composed of the individual structural masses of the components such as the wings, the fuselage, the vertical and horizontal tailplanes, the engines and so forth. Since payload mass is known from the mission, the fuel and operational empty mass of the aircraft need to be estimated. Roskam (2005) presents a method for calculating the required fuel weight for a given mission for a given type of aircraft based on historical data. This involves calculating the fuel fractions used in several different phases of flight from the known data, with the primary phase of cruise being calculated from an estimate using the Breguet range equation:

$$\mathbf{R_{CR}} = \frac{\mathbf{V_{CR}}}{\mathbf{C_T}}\left(\frac{\mathbf{L}}{\mathbf{D}}\right)_{\mathbf{CR}} \mathbf{log}\frac{\mathbf{W_{initial}}}{\mathbf{W_{final}}} \tag{12}$$

In this case the cruise range is dependent on the initial and final weights of the aircraft, the lift-to-drag efficiency of the aircraft, the cruise velocity of the aircraft and of course the specific fuel consumption of the aircraft. The lift-to-drag value is either assumed from empirical studies, or during the final analysis and comparison, taken from the aerodynamic calculations of the optimised configurations in the toolchain from the vortex-lattice tool.

The fuel-fractions method presented in Roskam (2005), in combination with initial estimates of lift-to-drag efficiency, as well as the specified mission parameters allow for a fuel mass estimate to be developed in terms of a fraction of the whole mass of the aircraft:

$$\mathbf{M_F} = (\mathbf{1} - \mathbf{M_{ff}})\mathbf{M_{TO}} + \mathbf{M_{FReserve}} \tag{13}$$

Where the mission fuel fraction is derived from the fuel fractions required for the various aspects of the mission, and the additional reserve fuel required is also taken into account. This allows the operational empty mass of the aircraft to be expressed as a function of the take-off mass of the aircraft. Given the reliable statistical data (Roskam, 2005) that is present that links the operational empty mass of the aircraft to the take-off mass of the aircraft, an iterative solution can then be derived based on initial guess values for take-off mass and operational empty mass for values that satisfy the statistical relationships between them for jet transport. Raymer (2012) presents an identical method for estimating the initial take-off mass of the aircraft, utilising the same statistical, historically-accurate relationships.

Further statistical mass fractions can then be used to estimate the weights of the various components of the aircraft (Roskam, 2005). For jet transport aircraft, a number of different aircraft are presented with the statistical breakdowns of the masses of various structural components that can be averaged to present a reasonable correlation for new aircraft. In this way the various component masses of the aircraft structure can be estimated from the overall initial MTOW of the aircraft.

3.3.2. Performance and Sizing

Similar equations and calculations also exist for the aircraft sizing. One example would be for the wing sizing, which is based off the wing loading during take-off and landing, with first estimate values for the mass and the maximum lift coefficient. According to Roskam (2005), these can be used to estimate the approach speed of the aircraft to the landing field based on statistical data and current design philosophies.

The approach speed ($\boldsymbol{V_a}$) must be calculated first:

$$\mathbf{V_a} = \sqrt{\left(\frac{\mathbf{S_{LFL}}}{\mathbf{0.34}}\right)} \tag{14}$$

And then using this, the landing speed of the aircraft can be estimated as again, statistical data and historical methods are of great use here:

$$\mathbf{V_a} = \mathbf{1.3V_{SL}} \tag{15}$$

The lift coefficient equation can then be transposed with this value used as the velocity to arrive at the initial value of the wing loading of the aircraft during the landing:

$$\left(\frac{\mathbf{W}}{\mathbf{S}}\right)_{\mathbf{SL}} = \frac{\mathbf{1}}{\mathbf{2}}\left(\frac{\mathbf{V_{SL}}^{\mathbf{2}}\mathbf{C_{Lmax_L}}\boldsymbol{\rho}}{\mathbf{9.81}}\right) \tag{16}$$

This can then be used to estimate the take-off wing loading, using the estimated take-off weight and landing weight (Roskam, 2005).

$$\left(\frac{\mathbf{W}}{\mathbf{S}}\right)_{\mathbf{TO}} = \frac{\left(\frac{\mathbf{W}}{\mathbf{S}}\right)_{\mathbf{SL}}\mathbf{W_{TO}}}{\mathbf{W_L}} \tag{17}$$

The higher wing load is then used to size the reference wing area of the aircraft, which can then be used to further size the wing, including the aspect ratio, span, chord (arising from the geometric relationship between aspect ratio and area) and other parameters such as horizontal tailplane surface area.

$$\mathbf{S_{HT}} = \frac{\mathbf{c_{HT}\bar{C}_W S_W}}{\mathbf{L_{HT}}} \tag{18}$$

3.3.3. Zero Lift Drag

The zero-lift drag of the aircraft was also calculated using a component build-up method in order to provide a first-order estimate that could be used for the aerodynamic and performance analysis of the conventional and box-wing configurations, as calculation of the zero-lift drag was not possible with the AVL software (Drela & Youngren, 2006). Instead, the component build-up method presented by Raymer (2012) was used to estimate the influence of the skin-friction drag of various aircraft components (fuselage, empennage, wings etc.) as well as the interference drag from how two components joined together that create more drag than the sum of their individual drags. This analysis is only suitable for aircraft in subsonic flow. This method of estimating the zero-lift drag was necessary for the analysis due to the importance of the drag in the aerodynamic performance and fuel burn calculations for the conventional and box-wing aircraft, and to ensure that the additional interference and friction drag effects from the box-wing planform were included in all analyses of that configuration so a better overall picture would emerge of the performance of the box-wing in comparison to the conventional.

The drag of each component of the aircraft is dependent on its form factor (FF), a skin-friction flat-plate drag coefficient (C_f), the interference factor (Q) and the wetted and reference areas. The miscellaneous component drag and the leaks and protuberances component drag were held identical across both conventional and box-wing configurations and hence were not as important the calculations. The subsonic zero-lift drag is hence:

$$\mathbf{C_{D_0} = \frac{\Sigma\left(C_{f_c}FF_cQ_cS_{wet_c}\right)}{S_{ref}} + C_{D_{misc}} + C_{D_{LP}}} \tag{19}$$

In this case the subscript c refers to the fact that each of those values are different for each component of the aircraft. The skin-friction coefficient depends on the flow over the component and how much of it is laminar and how much is turbulent (and hence dependent on the Reynolds number of the flow). The laminar flow skin-friction coefficient is:

$$\mathbf{C_f = \frac{1.328}{\sqrt{R}}} \tag{20}$$

While the turbulent coefficient is:

$$\mathbf{C_f = \frac{0.455}{(\log_{10} R)^{2.58}(1 + 0.144M^2)^{0.65}}} \tag{21}$$

Using a weighted average of the two, and estimating the percentage of laminar and turbulent flow along each component along with their respective Reynolds numbers estimated using the cut-off method, an average skin-friction coefficient can then be calculated (Raymer, 2012).

The skin-friction coefficient must be adjusted to take into account the drag caused by flow separation, dependant on the shape of the component. Considering both theoretical and empirical analyses, these form factors were derived (Raymer, 2012). For wings, tails, struts, and pylons, the form factor is:

$$\mathbf{FF = \left[1 + \frac{0.6}{\left(\frac{x}{c}\right)_{max}}\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4\right]\left[1.34M^{0.18}(\cos\Lambda_m)^{0.28}\right]} \tag{22}$$

Where the $\left(\frac{\mathbf{x}}{\mathbf{c}}\right)_{\mathbf{max}}$ refers to the chordwise location of the maximum thickness of the airfoil, the $\left(\frac{\mathbf{t}}{\mathbf{c}}\right)$ is the thickness-to-chord ratio of the airfoil and the $\mathbf{\Lambda_m}$ refers to the sweep of the maximum thickness line (Raymer, 2012).

For the fuselage and smooth canopy the form factor is

$$\mathbf{FF} = \left(\mathbf{1} + \frac{\mathbf{60}}{\mathbf{f^3}} + \frac{\mathbf{f}}{\mathbf{400}}\right) \tag{23}$$

And for nacelles and smooth external stores it is:

$$\mathbf{FF} = \mathbf{1} + \frac{\mathbf{0.35}}{\mathbf{f}} \tag{24}$$

Where the relevant factor is:

$$\mathbf{f} = \frac{\mathbf{l}}{\mathbf{d}} = \frac{\mathbf{l}}{\sqrt{\left(\frac{\mathbf{4}}{\boldsymbol{\pi}}\right)\mathbf{A_{max}}}} \tag{25}$$

Where the characteristic length of the relevant component ($\mathbf{l}$) and the maximum cross-sectional area presented to the flow ($\mathbf{A_{max}}$) are used to calculate the relevant values.

The interference factor is also based on historical, empirical evidence regarding the additional drag from two bodies that intersect such as the wing and the fuselage or the vertical and horizontal tails. The boundary layers of the flow along such intersections are thicker and cause more drag, hence the interference effects must be taken into account when estimating the zero-lift drag of the aircraft (Raymer, 2012). The interference factors suggested by Raymer (2012) vary for various aircraft components, including suggested values of 1.0 for the wing and fuselage and 1.04 for the tail. The wing-wing attachments between the vertical and horizontal wings of the box-wing planform would also have an interference factor, and for this conceptual design analysis, that value was estimated to be the same as for the tail interference of a conventional aircraft, as the two intersecting components are the most similar.

In summary, the contributions of each methodology to the empirical design analysis of the aircraft can be tabulated as follows:

Table 3-1 Methodology Contribution for Empirical Analysis

Analysis	**Method**
Weight estimate	Roskam
Performance and sizing	Roskam
Zero-lift drag estimate	Raymer

4. Methodology: Approach

4.1. Overview

The approach for the analysis requires integrating the aerodynamic and structural analysis and optimisation tools into a single toolchain that can then be used to conduct the overall fuel-burn comparison between the box-wing and conventional configurations for the different missions chosen. An overview of this process in form of a flow diagram is presented in Fig. 4-1.

The aerodynamic analysis requires the geometry and performance characteristics values derived from the mission requirements such as the velocity at the given altitude. This optimisation with the AVL tool leads to outputs which become inputs for the structural analysis using the WingMASS tool. Specifically, the wing twist necessary for the elliptical lift distribution is used to modify the wing geometry and the aerodynamic loads on the wing are used for the structural analysis.

Once the structural analysis is complete using the specified loadcases, the weight breakdown can be updated and recalculated using the new improved weight structure and the flow-on ancillary benefits of that improvement (reduced fuel load, for example). This aerostructural optimisation and analysis is conducted for the baseline conventional configuration for each mission, as well as the box-wing configurations that are generated by the geometric parameter sweep.

The update MTOW and cruise aerodynamic performance characteristics are both then inputs for the fuel burn analysis undertaken using Breguet's range equation, which is then the basis for the fuel burn comparison for the box-wing configurations compared to the conventional baseline for each of the missions.

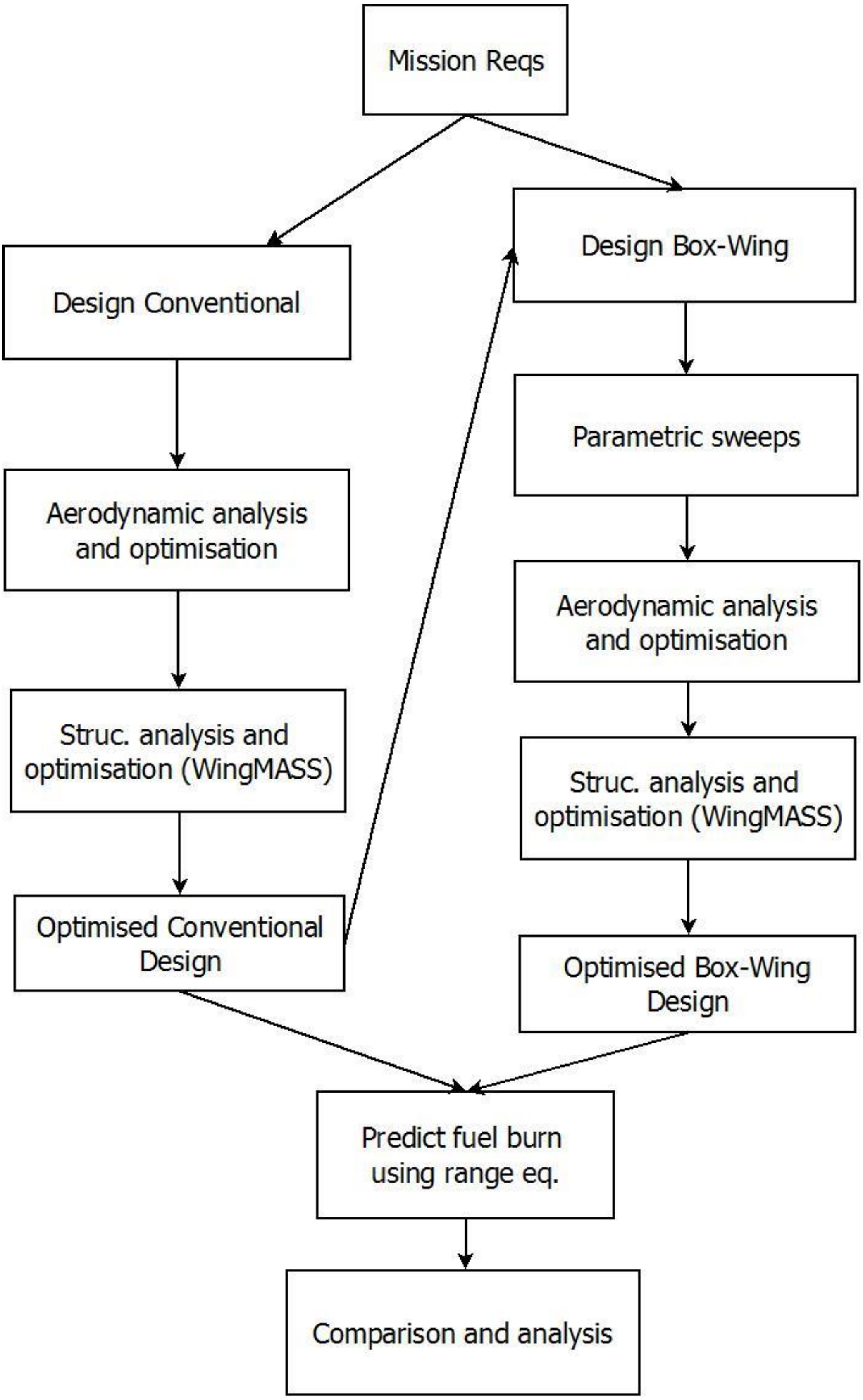


Figure 4-1 Flowchart overview of analytical approach

4.2. Missions and Specifications

In order to consider the optimum mission or niche for the box-wing concept, as outlined in the literature review, an exploration of the various mission requirements that influence the design of short-range aircraft is necessary. This will serve as a basis for developing the mission requirements for the analysis undertaken. The four parameters chosen to create these different missions are cruise altitude, mission range, cruise Mach number and number of passengers (payload for mission). These four allow a broad matrix of mission choices to be formed in order to consider the box-wing against the conventional configuration it would presumably replace, and allow for a picture to be formed from whence an assessment can be drawn as to which missions may suit the box-wing configuration the best, and what kind of advantage the box-wing could offer over that mission.

Since the focus of this analysis is on short-range missions, the ranges of the parameters have been chosen to realistically reflect the possible missions that are available and could be flown that would fit into that category. While the edges of the differences between different missions remain nebulous, the broad categories are fairly well understood.

Within those ranges, the most interesting possible combinations of missions that would serve as a basis for the preliminary design of the box-wing concept must be chosen. Here the values are chosen both maximum scientific interest, and on reflection from literature as to where the most advantage is gained for the industry and the environment in terms of changes to conventional design values. Looking outside the box offers advantages in terms of considering new mission niches that are not readily pursuable by current conventional designs.

4.2.1. Parameters

The chosen parameters of cruise altitude, cruise Mach number, mission range and number of passengers offer the best combination of conceptual design characteristics and mission parameters to vary. By considering a range in these values, the design space and the mission types that can be explored are broadened to a justifiable extent and yet remain within realistic boundaries for consideration. These parameters serve as the first principles of deriving a new mission for a new aircraft and will generally always be the first step or number to be considered when a designer approaches the problem or a customer is considering the final product.

Range determines the sector lengths and city pairs a given aircraft can fly, and the necessary fuel and other operational requirements for such an aircraft derive from this parameter. Since the focus here is on short-range missions for the box-wing concept, the maximum range considered is 2000 nautical miles and the minimum is 1000 nautical miles. Similarly, a cruise Mach number range was chosen with a lowest point of 0.7 and a highest point of 0.78, while the number of passengers was chosen between 100 to 200. Finally the cruise altitude values considered ranged between 5000 and 10000 meters.

Each of these will be detailed further in their respective sections, but the guiding criteria was always the focus on the chosen aircraft concept and the broad mission goal- a short-ranged city-hopper scenario where the strengths of the box-wing concept could hypothetically be maximized while staying within reasonable definitions of what such an aircraft may use as mission parameters while exploring possible untested niches in the market as explained in Chapter 2. Naturally, it must be remembered that all the parameters feed into each other and interact with each other as well.

4.2.2 Cruise Mach Number

The choice of cruise Mach number, at least at the upper bound, is partially determined by the chosen method of analysis, as outlined in the methodology section. Vortex-lattice methods generally break down in terms of accuracy and trustworthiness in the transonic region at around Mach 0.8, even using the Prandtl-Glauert correction. Hence, the maximum chosen for analysis is Mach 0.78, which is slightly slower than current aircraft flying these missions, yet would likely be the design point for aircraft designed specifically for short-ranged missions. The lower bound of the chosen range is set at Mach 0.7. To go lower than that would then start driving engine choice into a region where it would be impossible to compare with current aircraft flying some of those missions, and make engine choice and such issues added factors to complicating an already large design space.

However, there are some compelling arguments that exist with regards to considering cruise Mach numbers and lower values than those considered standard for existing aircraft, aimed at the best combination of fuel efficiency and passenger comfort for a given design scenario. This can be traced out in studies which calculate the benefits of lowering the Mach number by small values such as 0.02 or 0.03 from a nominal cruise Mach number (such as 0.8) as greatly reducing fuel burn while only increasing travel time or cost slightly (Filippone, 2007; Koch et al., 2011). Further studies indicate the strong impact on the environment and consequent fuel burn reduction such a change would have (Reynolds et al, 2010), while not having a particularly significant impact on travel times or passenger comfort when considering short-ranged, city-hopper missions (Filippone, 2007).

4.2.3 Cruise Altitude

Cruise altitude is also a parameter of choice that can be examined, especially in the case of short-range city-hopper missions with short flying times. In these cases, flying time spent ascending or descending to higher cruise altitudes can often be a waste of both time and fuel, and hence offer an opportunity to consider a range of values for this mission parameter.

A study by Williams, Noland and Toumi (2002) have shown that a reduction in cruise altitude can lead to minimal changes in flight time while offering significant environmental benefits while another and Reynolds et al. (2010) touch on this as well. A more in-depth study by Koch et al. (2011) showed that there are significant benefits possibly available in terms of reducing the environmental impact of air travel with only small impacts in terms of operating cost. Although based on a long-range aircraft and mission (Airbus A330 and Detroit-Frankfurt respectively), this study's insights are too valuable to ignore showing a steady and meaningful decline in overall environmental impact as lower altitudes were considered, up to greater than 30% (Koch, et al., 2011). For the given route and aircraft in that particular analysis, for a given direct operating cost increment of 10%, an operating point of 8534m altitude and cruise Mach number of 0.75 yields an average temperature reduction benefit of 28% (Koch, et al., 2011). This trade-off between the environmental impact of the aircraft and the fuel burn are an important consideration for the box-wing, which may well be able to offer the former advantages while overcoming the latter disadvantages.

Based on this it is straightforward to see that altitude considerations should be taken into this design investigation. The highest bound is 10,000 metres, similar to the current in-service aircraft in the closest mission niches, while the lower bound of 5000 metres lowers the altitude significantly in hopes of discovering the impact on the performance and savings offered both by a box-wing configuration and by an equivalent conventional one.

4.2.4 Passenger Capacity

A payload for a given mission serves as a large influence on the size and weight and hence fuel burn of any new concept considered for a particular mission. In this case again a wide range of passengers (PAX) were considered in order to explore a relatively wide design space, with an upper limit of 200 which is around the number carried by the extended range variants of the Airbus A320 and Boeing B737 families like the 737-900ER or A321, and a lower limit of a 150 passengers closer to their standard variants like the 737-700 or A320.

These typical mission loadouts offer a valid basis for comparison of the conventional and box-wing concepts developed against standard real-world aircraft in terms of passenger capacity and hence mission suitability. Naturally payload weight is a significant factor when considering wing sizing and optimal perfomance conditions, and the number of passengers are to influence that greatly. Being flexible in terms of passenger capacity also allows for a larger comparison in mission types, meaning the suitability of the box-wing concept can be better assessed over a bigger design space.

Furthermore, studies by the likes of Kenway et al (2010) have suggested that short-range aircraft with slightly-larger passenger number or loads may well be a a possible future design concept worth exploring, as it volume density of air traffic between city pairs in relatively close proximity increases in the future. Increasing the geometric distance between wings is also a posited to be a key design driver for the box-wing concept, and that can be explored more naturally when comparing aircraft of different sizes. Hence, the variation in the passenger load is chosen as a design variable for these missions.

4.2.5 Range

Range determines the sector lengths and city pairs a given aircraft can fly, and the necessary fuel and other operational requirements for such an aircraft derive from this parameter. Since the focus here is on short-range missions for the box-wing concept, the maximum range considered is 2000 nautical miles and the minimum is 1000 nautical miles. Considering the data collected from the Official Airline Guide (OAG Aviation Solutions, 2007) it can be easily seen that there are several key sector lengths that can be seen as operative especially for single-aisle aircraft such as the A320 or the B737.

Fig. 4-2 illustrates how the single-aisle aircraft portion of the market breaks down in terms of cumulative flights and their respective ranges. The bars correspond to the number of flights (in 1000s) made at the respective sector lengths indicated, while the curve tracks the total number of flights across all sector lengths as the sector length considered is increased.

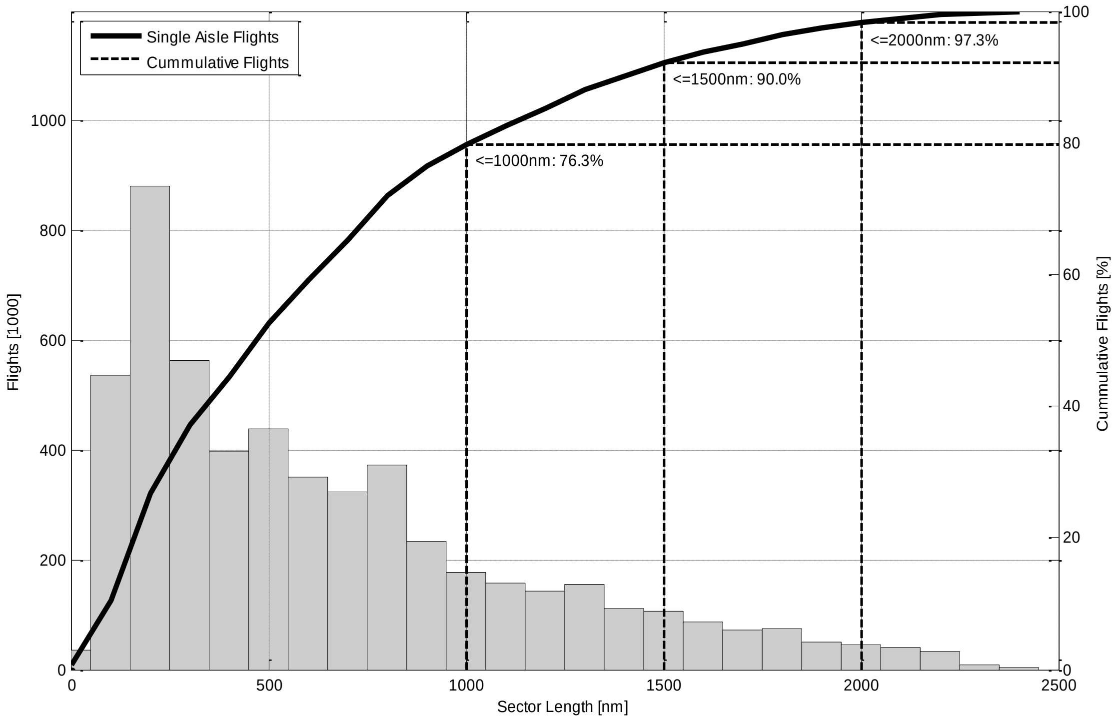


Figure 4-2 Cumulative flights versus sector length for twin-engine single aisle aircraft in 2007 (OAG Aviation Solutions, 2007)

Firstly, it can be seen that just over 75% of all single-aisle flights from the cumulative total operate in sectors that 1000 nautical miles or fewer apart. This is essentially means that aircraft operating those sectors which are optimised for longer rangers are in fact over-designed and will not be performing at maximum efficiency in terms of fuel burn and operating cost when used in such missions. Increasing that figure to 1500 Nm then captures 90% of all flights made by these aircraft, while increasing it again to 2000 Nm captures 97.3% of all flights made by single-aisle aircraft in this timeframe, virtually all of them.

Hence it can be seen that the vast majority of flights operate in a city-hopper, short-range scenario where the airports are less than a 1000 Nm apart. In terms of considering new mission scenarios and cruise ranges, focusing on this area of need and not overdesigning new concepts is something that should be considered by this and other future studies. Thanks to the fact that a proportionally larger percentage of such a flight would be spent in conditions conducive to the advantages of the box-wing (a larger proportion of the overall drag generated would be the induced drag), this shortest distance therefore appeals the most broadly to the concept. Reducing the design range of the aircraft of course reduces the fuel required and significantly reduces the weight of the aircraft overall, depending on the reduction in range and type of mission considered (Martinez-Val et al, 2010).

However, it is possible that increasing the range to capture a cumulatively larger proportion of flights may yet offer a beneficial outcome for the box-wing concept when considering it to against the conventional configuration. It would be remiss not to examine this possibility in term of exploring a larger design space for such aircraft.

Finally, there remains a more remote likelihood that a properly-designed box-wing configuration could indeed offer a viable alternative to single-aisle conventional aircraft across all sector lengths. Considering a cruise range of 2000 Nm allows a comparison against a conventional configuration that would most strongly resemble current and planned future aircraft of this type, and hence offer a basis for examining the real-world possibility of a box-wing design coming to fruition.

4.2.6 Configuration Choice

It can be seen that there are a variety of combinations that can be chosen as the mission parameters to drive the new configurations to be designed, however in the interests of efficiency, four different missions will be the main focus of this study. In order to incorporate the broadest range of the parameters, they will cover different mission niches:

<u>Mission 1:</u>

This mission has an aircraft capacity of 200 passengers for a design range of 2000 nm at a cruise Mach of 0.78 and a cruise altitude of 10,000 m. These design choices are all at the furthest maxima of their respective envelopes. The largest cruise range for the highest Mach number makes sense in terms of reducing flight time, while altitude is chosen to be high for this range due to the higher travel time and speed. Finally, the largest load ties into that as this aircraft will be able to cover the most distant city pairs in these sets of missions (and over 97% of all missions that single-aisle twin-engine aircraft flew a few years ago as per Fig 1.1), making it more attractive if it can carry larger amounts of passengers between those more distant cities. This aircraft also serves as the closest model to the currently operating aircraft models that fit this scenario, and will be used for comparison, calibration and validation of the tool chain and methodology.

Mission 2:

A true short-range cityhopper mission, this aircraft flies 1000 nm at a cruise Mach number of 0.7 and a cruise altitude of 5000 m, with a payload of 150 passengers. This concept pushes to the extremes in searching for the benefits of lower altitude and cruise Mach number, as well as the fact that three-quarters of all missions for aircraft this size are flown between destinations with within that design range (Fig 1.1). An audacious concept but one that may well allow for the full exploration of the box-wing's strengths in terms of maximizing the impact of reduced induced drag and minimizing environmental impact.

Mission 3:

A scaled-back concept mission from the first, this aircraft will still be based around a design range that takes into account 90% of all single-aisle, twin-engine airliner flights from 2007 (see Fig. 1.1), but taking into account some of the changes suggested in the research regarding the effects of lower flight altitude (7500 meters) and lower cruise Mach number (0.75) with regards to their environmental benefits. The lower passenger number, with a design load of 175 passengers, also refocuses the mission concept somewhat into a separate niche, allowing for an exploration of a possibly different kind of aircraft concept.

Mission 4:

A more radical concept, this mission focuses on combining the maximum passenger load at minimum range, offering the greatest load capacity but at the reduced range at which most twin-engine single-aisle airliner flights operate, with the environmental impact of reducing the cruise

Mach number and altitude without going to the extremes of the previous concepts. Hence the number of passengers was chosen as 200, the cruise Mach number of 0.73 tied into a chosen cruise altitude of 7500 meters and the design range was chosen to be the lowest value investigated, investigating if a short-range, larger-payload aircraft was where the box-wing offered the most efficiency in terms of the mission flown.

These four missions offer a broad overview of the reasonable design space of a new short-range concept and form the palette against which a box-wing configuration can be assessed with respect to a conventional aircraft.

Table 4-1 Summary of selected missions

	Number of Passengers	**Range**	**Cruise Mach Number**	**Cruise Altitude**
Mission 1	200	3704 km (2000 NM)	0.78	10000 m
Mission 2	150	1852 km (1000 NM)	0.7	5000 m
Mission 3	175	2778 km (1500 NM)	0.75	7500 m
Mission 4	200	1852 km (1000 NM)	0.73	7500 m

4.3 Conventional Design

The four mission requirements outlined earlier in this chapter are not sufficient to generate a design configuration. Additional requirements, such as landing field length must be specified to ensure that the aircraft that is designed conforms to real-world mission parameters and scenarios such as the types of airports it can operate from.

The first extra parameters that should be considered are the take-off and landing field length restrictions, as these have a large effect on the wing loading and sizing for initial consideration, and are critical in terms of airport operations. The take-off and landing field lengths were chosen based on real world single-aisle aircraft such as the Boeing 737 and Airbus A320, as these are the closest to performing the short-range cityhopper role in today's market. Furthermore, geometric boundaries such as the wingspan and height of the fuselage and tail are restricted to the values of these aircraft so that the dimensions important for airport usage and maintenance are not exceeded.

For the structural design of the conventional and box-wing configurations, it was clear that multiple loadcases and scenarios would inherently complicate and extend the problem. Hence a single phase of flight was chosen to be necessary aerodynamic condition of the analysis, which was the cruise phase. Even for short-range missions such as those being investigated here, the cruise phase still constitutes the majority of the flying time and distance. Hence, the aerodynamic loads used for the structural analysis, and the design of the box-wing and the conventional planforms themselves in terms of sizing and characteristics will be conducted around the cruise phase.

The loadcases for the structural design analysis also needed to be chosen. While a wide variety of loadcases could be used, each added would increase the computational time and resources required to complete the analysis. Furthermore, many of the more specialised loadcases depended on design parameters or scenarios that might not become relevant till the more detailed design of the configurations were tackled. Hence, in this case, two relatively important and straightforward loadcases were chosen for this task, both adhering to the relevant Federal Aviation Regulation (FAR) 25 design criteria for passenger aircraft. Those chosen criteria are for cruise flight, where it is mandated that the sizing of the wing be done for the operating loads with factors of +2.5g and -1.0g. At the conceptual design stage of the aircraft design study, this is a commonly used set of loadcases for structural design and analysis, and indeed sometimes is simplified further to the 2.5g case (Jemitola, et al., 2013). For this investigation, the WingMASS tool was tested and found robust enough and quick enough to handle both loadcases for both the conventional, and more critically, box-wing configurations and hence both were implemented and used for the structural sizing and optimisation loop when the analysis was conducted. The structural materials used for both conventional and box-wing aircraft will be relevant metal alloys, such aluminium 7075 for the spars and aluminium 2024 for the skin.

Engine choice was also kept the same for both configurations, with a relevant choice of parameters that might serve as a future engine for this aircraft used as the basis of comparison. Again engine design and optimisation with the configuration is a relatively large and complex design issue that falls outside the scope of the investigation. The CFM-56B engine that is standard and used on the Airbus A320 aircraft is used for the performance calculations across all mission scenarios and aircraft.

Based on these assumptions and requirements then the first design task, that of sizing the conceptual conventional configuration that would fly a mission relatively optimally can then be undertaken. Using the multidisciplinary approach, tools and methodology outlined, the structural and aerodynamic considerations can be combined into a single approach in the concept design phase to give the design team an insight into whether a conventional or box-wing planform is suited to the mission requirements at hand.

The statistical and historical data and equations that were presented in the previous chapter were used to size and design the conventional configuration for each of the missions used. Once the conventional configuration was initially sized using this method, it was implemented into the developed aerodynamic and structural toolchain as described in Chapter 3. There, the wing was optimised for aerodynamic and structural efficiency. As the wing was already sized and designed with efficiency in mind, the aerodynamic optimisation required via wing twist at this conceptual design stage was absolutely minimal. In turn the aerodynamic loads calculated during this process were applied to the WingMASS tool, and then used to kick-start the WingMASS optimisation loop for the wing structure. The results of that optimisation were then checked for any discrepancies regarding lift distribution, load analysis, stability characteristics and so forth, and once deemed suitable could then be used to calculate the new weight of the wings and re-calculate the overall estimated MTOW of the conventional aircraft.

The zero-lift drag of the aircraft was then calculated using the component build-up method also presented in Chapter 3, resulting in an estimate for the aerodynamic performance of the aircraft for analysis once the aerodynamic optimisation was complete.

4.3.1 Design Build-Up

The conventional configuration was designed and optimised using the process outlined above and in Chapter 3 where the mathematics and equations behind the historical, statistical design process are presented. As an example case, the design build-up of the conventional design for Mission 2 is presented here, though each of the missions required their own set of calculations. For ease of reference, the calculations in this section are presented entirely in SI units though where required for comparison to historical data they were converted to imperial units and back again. The process begins with the chosen design parameters:

Table 4-2 Summary of initial design parameters for Mission 2

Number of passengers	150
Range (NM)	1000
Cruise Mach number	0.7
Altitude (m)	5000
Taper Ratio (wing)	0.25
Take-off field length (m)	2180
Landing field length (m)	1500

The design process and methodology for conventional aircraft based on historical and statistical data is based on a converging iterating process after initial guess values from current generation aircraft. Once many of the key aerodynamic and structural parameters have been initially sized and estimated, they are then entered into the aircraft design toolchain and methodology developed incorporating AVL and WingMASS. This was used to ensure that the wing has the optimum elliptical lift distribution via the wing twist, considering the lift and induced drag coefficients, and then further optimised structurally using the WingMASS tool so a more efficient wing structure was in place and improved the wing's structural weight. After this, the optimised values for wing weight and new maximum take-off weight are reiterated again through the process outlined till they converge and lead to a final set of values which are then used for the comparison against the box-wing model with the fuel burn calculations. This ensure the aircraft meets all the mission requirements in as optimal a manner as possible so it is not over-designed

The final iteration is presented here for clarity, with these values already have been iterated and converged via the toolchain and methodology presented. The first value that is required is that of the payload mass. For a single-aisle conventional design with six-abreast configuration in two classes, a total passenger number of 150 at 95 kilos each (passenger and baggage) means that the payload mass can be calculated.

$$\mathbf{M_{payload} = 150 \times 95 = 14250\ kg}$$

This is also the design payload for the A320, which carries the same number of passengers. Per Roskam (2005), this allows for an initial guess of take-off mass considering the range, the payload mass and the required cruise Mach number. The design take-off mass for the A320 is 73500 kg, however that aircraft has a much longer design range, and hence the guess for take-off mass takes that into the account.

$$\mathbf{M_{TOguess} = 70770\ kg}$$

From here, each segment of the mission is assigned a ratio between the weight of the aircraft at the beginning and at the end of the segment per historical data collected on jet airliners (Roskam, 2005). There are a number of segments modelled in detail including engine idle, loiter and flight to alternate airport. For this initial conceptual design study however, this was simplified into a smaller number of mission segments and the missions fractions for each were found via the statistical data provided (Roskam, 2005). The only exception is the cruise phase of the mission, where the fuel burned can be found via the Breguet range equation. Substituting the relevant numbers, with a lift-to-drag estimate of 11.8, into the equation shows

$$\mathbf{R_{CR} = \frac{V_{CR}}{C_T}\left(\frac{L}{D}\right)_{CR} \log\frac{W_{initial}}{W_{final}}} \qquad \textbf{(12)}$$

$$\mathbf{\log\frac{W_{initial}}{W_{final}} = \frac{1852000}{\frac{224}{1.833x10^{-5}} \times 11.8} = 0.0929}$$

Hence the ratio of the final weight to the initial weight over the cruise segment can be found.

$$\frac{\mathbf{W_{final}}}{\mathbf{W_{initial}}} = \frac{\mathbf{1}}{\mathbf{e^{0.0929}}} = \mathbf{0.911}$$

The following ratios presented in Table 4-3 show the mission fuel breakdown as estimated using Roskam's methodology (2005). The ratios for the other phases are drawn from tables and graphs shown in that reference.

Table 4-3 Weight ratios for each mission phase per Roskam (2005)

Phase	**Ratio**
Taxi	0.990
Take-off	0.995
Climb	0.980
Cruise	0.911
Reserve	0.960
Descent	0.990
Landing	0.992

From these ratios, an overall mission fuel fraction can then be used to estimate the fuel burned over the course of the mission (Roskam, 2005).

$$\mathbf{M_{ff}} = (\mathbf{0.990}) \times (\mathbf{0.995}) \times (\mathbf{0.980}) \times (\mathbf{0.911}) \times (\mathbf{0.960}) \times (\mathbf{0.990}) \times (\mathbf{0.992}) = \mathbf{0.83}$$

Then this value can be used to estimate the mass of the fuel as the reserve fuel is included in the fuel fraction calculations (Roskam, 2005).

$$\mathbf{M_F = (1 - M_{ff})M_{TO} + M_{FReserve}} \tag{13}$$

$$\mathbf{M_F = (1 - 0.83)M_{TO} = 0.17M_{TO}}$$

Hence a value for the operational empty mass is found taking into account the payload as well (Roskam, 2005).

$$\mathbf{M_{TO} = M_{OE} + M_F + M_P} \tag{11}$$

$$\mathbf{M_{OE} = 70770 - (0.17 \times 70770) - 14250 = 44489kg}$$

From Roskam's (2005) historical data figures, it is found that this is an allowable empty mass and the values converge, and the calculation and analysis can continue based on this take-off mass. The component mass fractions of the rest of the aircraft are also important, as the optimisation procedure analysed and re-sized the wing, and the rest of the structure must be estimated and held steady for the box-wing aircraft. There are several methods available to do this, but the statistical data outlined in Roskam (2005) from historical aircraft is sufficient at this initial conceptual design stage.

Using data gathered on the Airbus A320 and Boeing 737 from (Roskam, 2005) (Raymer, 2012) and internal Airbus data available to DLR, an averaged mass fraction for each of the main components of the aircraft was found, including the fuselage, wings, empennage and engines. The mission equipment mass accounts of the mass fractions of the aircraft's systems, pylons, crew, landing gear, cabin equipment and so forth. These mass fractions vary depending on the mission requirements for each conventional aircraft designed.

$$\mathbf{M_{Fuselage} = 0.124 \times 70770 = 8775\ kg}$$

$$\mathbf{M_{HT} = 0.011 \times 70770 = 778\ kg}$$

$$\mathbf{M_{VT} = 0.010 \times 70770 = \ 707\ kg}$$

$$\mathbf{M_{Equipment} = 0.277 \times 70770 = 19577\ kg}$$

The engine mass was of course based on the known manufacturer data, while the wing structural mass was found from the WingMASS optimisation tool's output and then recalculated with the other wing component masses to find the overall wing mass.

$$\mathbf{M_{Engines} = 4800\ kg}$$

$$\mathbf{M_{Wing} = 9852\ kg}$$

The aerodynamic and performance based sizing is conducted in parallel with the initial structural analysis. For example, using equation 10, the wing loading for can be calculated the using the landing field length and historical data by first calculating the approach speed (Roskam, 2005).

$$\mathbf{V_a = \sqrt{\left(\frac{S_{LFL}}{0.34}\right)}} \tag{14}$$

$$\mathbf{V_a = \sqrt{\left(\frac{1500}{0.34}\right)} = 66.42\ m/s}$$

Which can then be used to the calculated landing speed per equation 11.

$$\mathbf{V_a = 1.3V_{SL}} \tag{15}$$

$$\mathbf{V_{SL} = \frac{66.42}{1.3} = 51.01\ m/s}$$

Which in turn means the wing loading can be calculated per equation 12.

$$\mathbf{\left(\frac{W}{S}\right)_{SL} = \frac{1}{2}\left(\frac{{V_{SL}}^2 C_{Lmax_L}\rho}{9.81}\right)} \tag{16}$$

$$\mathbf{\left(\frac{W}{S}\right)_{SL} = \frac{1}{2}\left(\frac{51.01^2 \times C_{Lmax_L} \times 1.225}{9.81}\right) = 162.46C_{Lmax_L}}$$

Then using equation 13, the wing loading at take-off can estimated using the calculated landing wing loading. Per Roskam (2005), the typical landing weight of transport jet is related statistically to its take-off weight.

$$\mathbf{W_L = 0.84W_{TO}}$$

$$\left(\frac{\mathbf{W}}{\mathbf{S}}\right)_{\mathbf{TO}} = \frac{\left(\frac{\mathbf{W}}{\mathbf{S}}\right)_{\mathbf{SL}} \mathbf{W_{TO}}}{\mathbf{W_L}} \tag{17}$$

$$\left(\frac{\mathbf{W}}{\mathbf{S}}\right)_{\mathbf{TO}} = \frac{\left(\frac{\mathbf{W}}{\mathbf{S}}\right)_{\mathbf{SL}} \mathbf{W_{TO}}}{\mathbf{W_L}} = \frac{\mathbf{162.46C_{Lmax_L}}}{\mathbf{0.84}} = \mathbf{193.4C_{Lmax_L}}$$

The maximum lift coefficient during landing can vary greatly depending on wing design, however a value must be chosen so the wing can be sized accordingly. Assuming a value of 3.0, as per latest conventional aircraft designs, leads to a critical take-off wing loading.

$$\left(\frac{\mathbf{W}}{\mathbf{S}}\right)_{\mathbf{TO}} = \mathbf{595.2\ kg/m^2}$$

Which then leads to the wing area (Roskam, 2005).

$$\mathbf{S = \frac{70770}{595.2} = 118.9\ m^2}$$

One of the key parameters in aircraft design is the aspect ratio of the wing, which is generally between 9 and 10 for jet transport aircraft. The aspect ratio was chosen initially based on statistical and historical values, and then re-iterated and optimised using both geometric boundaries (ensuring the wingspan did not exceed that of real world aircraft such as the A320) as well as internal DLR methodology. The final optimised value of 9.87 allows the wingspan to be sized.

$$\mathbf{b = \sqrt{9.87 \times 118.9} = 34.3\ m}$$

Which then can be used to size other parts of the aircraft, such as the horizontal tail. Raymer (2012) uses volume coefficients based on historical data from Roskam (2005) to initially size the horizontal and vertical tail. The other values required for this calculation include the length of the moment arm, so the length of the fuselage must be estimated using methodology presented in Raymer (2012) and Roskam (2005) and calibrated by measured data from Airbus available to DLR. From this the fuselage length is calculated.

$$\mathbf{l_{fuselage} = 37.5\ m}$$

The lift and induced drag coefficient are calculated using the vortex lattice method applied via the AVL software, but the zero-lift drag must be estimated by the component build-up method presented in Raymer (2012) for the cruise flight condition. The miscellaneous component drag and the leaks and protuberances component drag were held identical across both conventional and box-wing configurations and hence were not as important the calculations. The subsonic zero-lift drag is hence:

$$\mathbf{C_{D_0} = \frac{\Sigma\left(C_{f_c} FF_c Q_c S_{wet_c}\right)}{S_{ref}} + C_{D_{misc}} + C_{D_{LP}}} \tag{19}$$

For the initial conceptual design and estimation, this term can thus be simplified down to

$$\mathbf{C_{D_0} = \frac{\Sigma\left(C_{f_c} FF_c Q_c S_{wet_c}\right)}{S_{ref}}}$$

For each component such as the wings, the fuselage, the horizontal tailplane and the vertical tailplane this value must be calculated. In this case, the calculation for the fuselage is presented. The laminar flow skin-friction coefficient for the fuselage is based on Reynold’s number during cruise (Raymer, 2012).

$$\mathbf{R_{fuselage} = \frac{v \times l_{fuselage}}{\upsilon} = \frac{224 \times 37.5}{2.21\mathit{x}10^{-5}} = 3.80\mathit{x}10^{8}}$$

$$\mathbf{C_{f_{fuselageL}} = \frac{1.328}{\sqrt{R}}} \tag{20}$$

$$C_{f_{\mathbf{fuselageL}}} = \frac{\mathbf{1.328}}{\sqrt{\mathbf{3.80x10^{8}}}} = \mathbf{6.82x10^{-5}}$$

While the turbulent coefficient is:

$$C_{f_{\mathbf{fuselageT}}} = \frac{\mathbf{0.455}}{(\mathbf{log_{10}\,R})^{\mathbf{2.58}}(\mathbf{1+0.144M^{2}})^{\mathbf{0.65}}} \quad \textbf{(21)}$$

$$C_{f_{\mathbf{fuselageT}}} = \frac{\mathbf{0.455}}{(\mathbf{log_{10}\,R})^{\mathbf{2.58}}(\mathbf{1+0.144M^{2}})^{\mathbf{0.65}}}$$

$$C_{f_{\mathbf{fuselageT}}} = \frac{\mathbf{0.455}}{(\mathbf{log_{10}(3.80x10^{8})})^{\mathbf{2.58}}(\mathbf{1+0.144(M0.7)^{2}})^{\mathbf{0.65}}} = \mathbf{0.0017}$$

For the weighted average, the percentage of the fuselage where the laminar flow applied was assumed to be 10% and the rest was assumed to be turbulent as per Raymer (2012). Thus the weighted average of the two could calculated.

$$C_{f_{\mathbf{fuselage}}} = \left(\mathbf{6.82x10^{-5}} \times \mathbf{0.1}\right) + (\mathbf{0.0017} \times \mathbf{0.9}) = \mathbf{0.0015}$$

The skin-friction coefficient must be adjusted to take into account the drag caused by flow separation, dependant on the shape of the component. Considering both theoretical and empirical analyses, these form factors were derived (Raymer, 2012). For the fuselage the form factor is

$$\mathbf{FF} = \left(\mathbf{1} + \frac{\mathbf{60}}{\mathbf{f^{3}}} + \frac{\mathbf{f}}{\mathbf{400}}\right) \quad \textbf{(23)}$$

Where the relevant characteristic value is:

$$\mathbf{f} = \frac{\mathbf{l}}{\mathbf{d}} \quad \textbf{(25)}$$

With the fuselage diameter able to be calculated from the seating arrangement and the passenger load, the value is hence

$$\mathbf{f_{fuselage}} = \frac{\mathbf{37.5}}{\mathbf{4.1}} = \mathbf{9.15}$$

Therefore, the form factor is

$$\mathbf{FF_{fuselage}} = \left(\mathbf{1} + \frac{\mathbf{60}}{\mathbf{9.15^3}} + \frac{\mathbf{9.15}}{\mathbf{400}}\right) = \mathbf{1.101}$$

The interference factor for the fuselage is generally thought to be negligible, and hence the overall zero-lift drag contribution of the fuselage in the cruise condition can be calculated.

$$\mathbf{C_{D_{0fuselage}}} = \mathbf{C_{f_{fuselage}}} \times \mathbf{FF_{fuselage}} \times \mathbf{Q_{fuselage}} \times \mathbf{S_{wet_{fuselage}}}$$

$$\mathbf{C_{D_{0fuselage}}} = \mathbf{0.0015} \times \mathbf{1.101} \times \mathbf{1} \times \mathbf{488.9} = \mathbf{0.81}$$

This is then summed with the other contributions to the zero-lift drag from the other components, calculated using the same methodology.

$$\mathbf{C_{D_{0wing}}} = \mathbf{0.79}$$

$$\mathbf{C_{D_{0htp}}} = \mathbf{0.06}$$

$$\mathbf{C_{D_{0vtp}}} = \mathbf{0.07}$$

$$\mathbf{C_{D_{0engine}}} = \mathbf{0.14}$$

In addition, the miscellaneous drag contribution can be estimated using historical and statistical values (Raymer, 2012) and entered into equation 15.

$$\mathbf{C_{D_0}} = \frac{\mathbf{0.81 + 0.79 + 0.07 + 0.06 + 0.14}}{\mathbf{118.9}} + \mathbf{0.0063} = \mathbf{0.022}$$

After that is complete, the conventional configuration design for this particular mission is complete and can be used as a baseline to design and compare with the box-wing configuration for this model. A summary of the aircraft characteristics is presented below in Table 4-4.

Table 4-4 Final design outputs for conventional configuration for Mission 2

Maximum take-off mass (kg)	70770
Wing area (m^2)	118.9
Wingspan (m)	34.3
Aspect ratio	9.87
Wing loading (kg/m^2)	595.2
Zero-lift drag coefficient	0.022
Lift-to-drag ratio in cruise	11.8

It is notable that the final lift-to-drag ratio in cruise is significantly lower for this aircraft compared to other jet airliners, more comparable to regional transport aircraft. However this is to be expected given that the mission requirements it is designed for are significantly less aerodynamically demanding (much lower altitude, range, cruise velocity etc.) and hence the lift-to-drag ratio does not need to be very high in order to perform the mission optimally.

4.4 Box Wing Model

After the relatively straightforward process of designing the conventional configuration based on historical and statistical data and straightforward design methodologies, the box-wing design process for the same chosen mission criteria is not as straightforward. As outlined in the previous chapters, a multidisciplinary analysis and optimisation approach must be applied so a relatively credible design process coalesces and the results prove to be helpful in terms of determining the future viability of the box-wing and the missions to which it is best suited.

In order for there to be an effective comparison between the different configurations, some basic parameters must be kept constant. The most relevant and useful one for this kind of comparison is reference wing area, around which the twin horizontal wings of the box-wing configuration can then be designed. The wing area was used as the reference parameter as it is driven by take-off distance and would not be affected by cruise performance. Hence the initial basic parameter for sizing the box-wing can be the wing area requirement, as the historical and statistical data used in the previous section is not applicable for the design of the box-wing planform.

As well as choosing the reference design parameter, the parameters that are to be varied so the scope of the design space is explored relatively fully must also be chosen. The horizontal and vertical separations between the two wings are two clear choices. The influence of the aspect ratio of the individual wings on the aerodynamic and structural characteristics of the planform must also be investigated- namely is the structural penalty trade-off for aerodynamically superior wings worth more or less when it comes to the box-wing planform than the conventional planform. Necessarily, of course, this involves varying the chords and spans of the individual wings of the box-wing. Aspect ratio uses the span and wing area of a single wing.

Thus, wing twist optimisation is necessary so that the elliptical and equal lift distribution on both wings can be achieved as demanded by the Prandtl-Munk theorem (Frediani, 2005). Each of the two horizontal wings were optimised separately to maintain the equal lift distribution by modifying the angle of twist along the span of the wing at different stations, while controlling the optimisation to ensure that the optimisation angles stayed within realistic bounds and did not vary by more than a single degree between each station. The optimisation was undertaken by modelling the required lift elliptically on each wing using the equation for an ideal ellipse

$$\left(\frac{\mathbf{x}}{\mathbf{a}}\right)^{2}+\left(\frac{\mathbf{y}}{\mathbf{b}}\right)^{2}=\mathbf{1} \qquad \textbf{(26)}$$

Where $\mathbf{x}$ and $\mathbf{y}$ are the respective geometric co-ordinates and $\mathbf{a}$ is the semi-major axis, in this case the wing span and $\mathbf{b}$ is the semi-minor axis, in this case the lift at the root of the wing and dependent on the overall lift from the wing that the designer wants. Using this relationship, a function can be derived for $\mathbf{y}$ in terms of $\mathbf{x}$, which can then be used as the basis for the optimisation of the lift distribution. The wing is divided into 10 stations along the span, with each section having its own independent twist angle, all of them initially at 0. The optimiser runs by working its way along the span of the wing, checking the difference between the optimal elliptical load distribution and the load at the section of the wing. If it is lower than the optimum, the twist angle is increased. If lower, the twist angle is decreased. The twist angles are not allowed to be greater than 8 degrees or lower than -8 degrees, while each section must be within one degree of the sections next to it. Finally, the optimiser stops when the difference at each section is less than 10% to the optimal elliptical lift distribution. It is looped continuously over the entire span of the wing till it conforms (bar the final section, where the horizontal wing meets the vertical wing of the box-wing, where the lift distribution cannot go to zero). The structural analysis and optimisation process, in contrast, is described in detail in section 3.2.2.

The horizontal and vertical separation measurements are shown in Figs. 4-3 and 4-4, while the combination of geometric parameters examined are best visualised by comparing box-wing models with the extremes of each of the geometric parameters. This shows the range of realistic values examined and how they actually impact the designs analysed for this study.

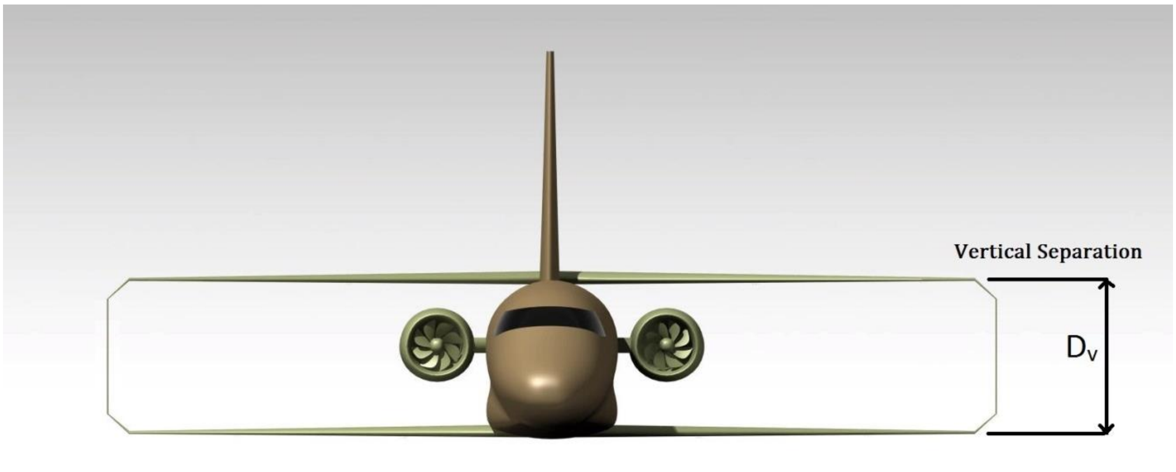


Figure 4-3 Vertical wing separation D_v

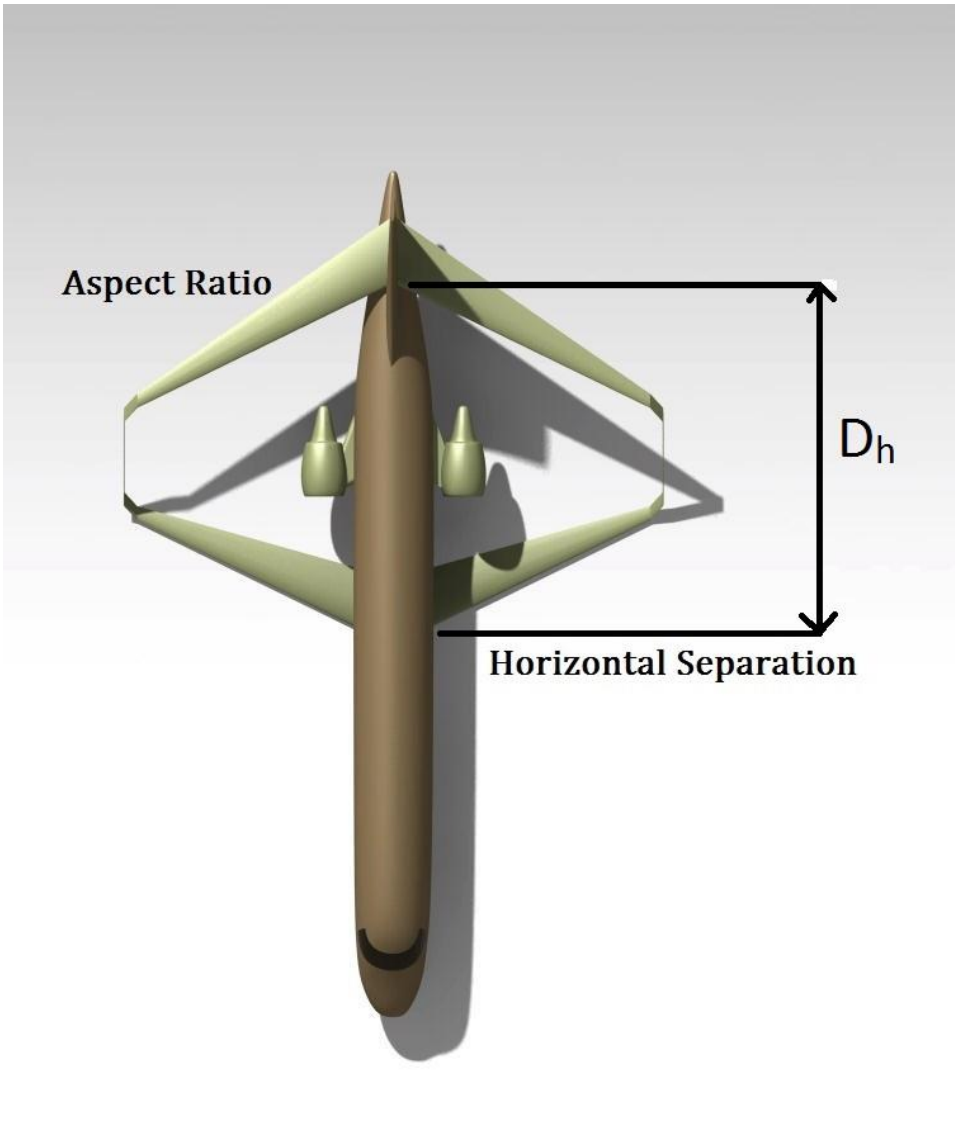


Figure 4-4 Aspect ratio and horizontal wing separation D_h

However, other variables must be frozen in order to limit the scope of the investigation and allow for effective and efficient computational efforts in terms of the investigation being conducted. For example, airfoil choice and optimisation is generally considered an important part of the design process for any wing system, let alone an unconventional design such as the box-wing. However the critical data needed for such an investigation (including computational fluid dynamics meshing and analysis) and the complexity of it would probably demand an entire separate research project of its own. Hence in this case the airfoil for both the conventional and the box-wing was frozen at the same sub-optimal choice (a NACA2412 airfoil that reduced the computational load on the analysis tools thanks to its simplicity and relative resemblance to real world airfoil shapes). Other geometric parameters such as taper of the wings were also frozen at the value used by the conventional configuration in the interests of simplifying the analysis down to the most vital parameters and isolating their influence on the aerodynamic and structural characteristics of the box-wing configuration.

There is another challenge that exists with regards to the wings of the box-wing configuration, which comes with splitting up the lifting area over two wings and hence leading to wings with smaller chords than conventional configurations. This can mean a number of different issues for the wing design, including the fact that there are significant changes in the Reynolds number effects and the structural impacts of have less space and volume for control surfaces, fuel systems, de-icing systems and so forth. While these effects are not captured in this initial study, they are vital and must be recognised and considered in future detailed design studies of the optimal configurations considered here.

The fuselage design is also of lesser importance when comparing these two configurations. Unlike other unconventional configurations such as the blended wing body, the box-wing configuration does not require a radical redesign or overhaul of the fuselage when compared to the baseline conventional configuration it is based off. Instead the same fuselage can be held constant for both aircraft, as the payload and number of passengers that both configurations are being designed for are identical and the structural implications on the fuselage itself from the box-wing configuration at this early stage in the design process are relatively minimal. The length and estimated weight of the fuselage varies between missions due to the difference in payload, but not for the geometric parameter sweeps for each mission.

The design of the horizontal and vertical tailplane is of more immediate concern. Other box-wing design studies have shown the peculiarities of the box-wing design, in terms of the structural and stability concerns, can have a broad impact on the design of the vertical tailplanes. The structural impact comes from the fact that the vertical tail often needs to support and anchor the rear wing, if it is too high to be supported structurally through the fuselage. This can lead to a vertical tailplane that needs to be strengthened and hence made heavier for the box-wing configuration as opposed to the conventional configuration. In terms of stability, the fact that there is a lifting surface at the rear of the aircraft, generating upwards lift can be problematic. In conventional aircraft, the horizontal tailplane actually generates downforce, counterbalancing the lift generated by the wings and ensuring the aircraft is stable and manoeuvrable. In the case of the box-wing, this is not possible as the conditions for aerodynamic efficiency require both wings to generate equal lift. Some studies (Frediani, 2005), (Jemitola, et al., 2013) have proposed a v-tail system at the rear for the box-wing, allowing for control devices to be implemented on the vertical tailplanes at the rear to try and overcome this disadvantage. Others have stuck with the standard vertical tailplane.

Once again, the design and study of a complete horizontal and vertical tailplane system and its effect on the overall aircraft design could form a significant research project in its own right. In this case, the size of vertical empennage is held steady as the box-wing configuration is designed and analysed in comparison to the conventional, at least initially. This allows for the focus of the investigation to hold on the wings themselves, the most unique and interesting change in the configuration, and the part that must be modified and optimised first if the box-wing is to have any initial theoretical advantage over the conventional. However, the weight is modified and raised slightly for configurations where the rear wing is attached to the vertical tailplane, to account for the greater structural strength needed to support the rear wing through the structural design. This value was based on discussions with aircraft structural design experts at DLR and Airbus as well classical literature on T-tail designs (Byrnes, et al., 1966) to maximum of 15% greater vertical tail weight for the maximum vertical separation. This value was reduced to 10% greater weight when the rear-wing was situated part of the way up the vertical tailplane, and came to zero when the rear wing was at the top of the fuselage and not attached to tail at all.

The integration of the landing gear purely into the fuselage imposes a structural penalty for those designs where it cannot be integrated into the lower surface of the wing. In the case of the box-wing designs, there would be an additional structural penalty from that for certain designs where it would not be possible to integrate the landing gear because of the wing placement changing for aero-structural optimisation reasons. In this study, that weight penalty was not imposed but it must be taken into account when higher-fidelity designs are analysed.

Another part of the box-wing planform that is necessary but challenging to estimate is the coefficient of zero-lift drag. The additional drag components arising for the box-wing, such as the added friction drag and interference drag from the vertical winglets, are added to the zero-lift drag already estimated for the conventional. Hence the overall zero-lift drag for the box-wing planform is greater than that of the conventional planform designed for the same mission, and any analysis comparing them both should attempt to involve both sets of drag values in order to present a more even overall picture of the aerodynamic characteristics of both configurations for comparison. The component build-up drag methodology that was used for this estimation was outlined in Chapter 3.

4.4.1 Horizontal Wing Separation

The first set of box-wing planforms kept the vertical wing separation and aspect ratio constant and investigated the influence of the horizontal wing separation on the aerodynamic and structural characteristics. A range of values for the horizontal separation were chosen with regards to keeping a realistic configuration in mind, and minimising the influence of the wings on each other's airflow via downwash- having the wings too close to each other horizontally led to interference effects which had a large negative influence on the aerodynamic performance of the whole wing planform. Another consideration here was the position of the centre of gravity and the landing gear, which meant the wings could not be too close together, with the front wing shifting backwards as the rear wing had to be placed next to the vertical tailplane. A level of freedom was still included in the design space exploration in order to consider the maxima and minima given purely aerostructural considerations, but the placement range kept realistic thanks to those additional design concerns in order to ensure there was no investigation of truly unfeasible results. The separation was measured as the horizontal distance from the leading edge of the root of the front wing to the leading edge of the root of the rear wing, in metres.

Table 4-5 Selected horizontal wing separation values

Parameter	Values (m)
D_h	14, 16, 18 and 20

4.4.2 Vertical Wing Separation

Vertical wing separation has a theoretically large effect on the aerodynamic and structural efficiency of the box-wing planform as per the literature review in Chapter 2. Here the effect of varying the vertical wing separation was considered, with the aerodynamic advantages to be considered against the structural disadvantages to combine into an overall result of how the geometric parameter affected the design. The separation was measured as the vertical distance from the tip of the root airfoil to the tip of the root airfoil, in metres.

Table 4-6 Selected vertical wing separation values

Parameter	Values (m)
D_v	4, 6, 8 and 10

4.4.3 Aspect Ratio

The aspect ratio was varied from a value of 7.5 to 11.5, for each wing for the first mission. Of course varying the aspect ratio also meant varying the entire geometry of the wing, including the wingspan and the chords. The mean aerodynamic chord was recalculated for each different planform to ensure the aerodynamic analysis was conducted as accurately as possible as well. The maximum value meaning that the wingspan did not extend beyond realistic values for the airports the aircraft might service as it was held at the wingspan of the conventional configuration, while for values lower than the minimum here, an investigation found that the aerodynamic characteristics and performance of the aircraft would not be of an acceptable level. The configurations for the other missions differed slightly in the values of the aspect ratio investigated, as the median value was dependent on the aspect ratio of the conventional configuration designed for the mission and the other values were based on that aspect ratio.

Table 4-7 Aspect ratio values investigated for Mission 1

Parameter	Values investigated
Aspect ratio of each wing	7.5, 8.5, 9.5, 10.5 and 11.5

The following diagrams present a visual example of the range of the design space investigated for the box-wing configuration, illustrating the change in the vertical and horizontal separation for wing planforms with the highest and lowest aspect ratios investigated and how that changes the configuration overall.

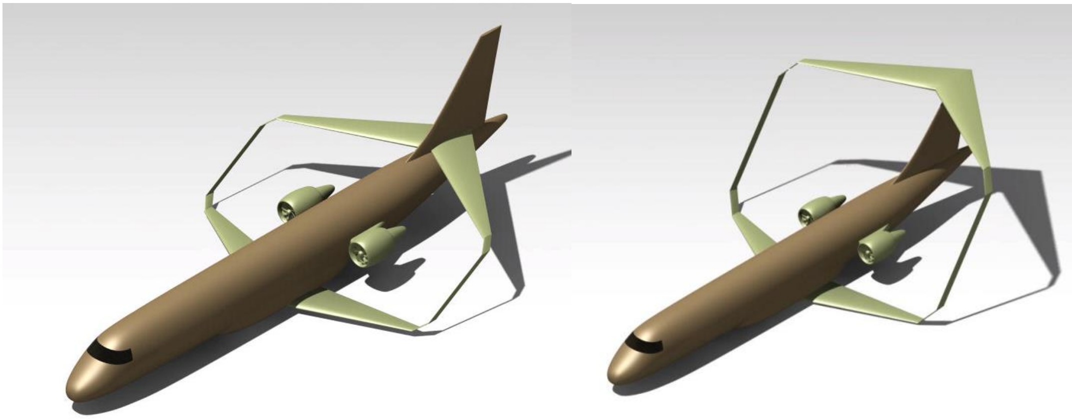


Figure 4-5 Aspect ratio 7.5, horizontal wing separation 14 metres and vertical wing separation 4 & 10 metres

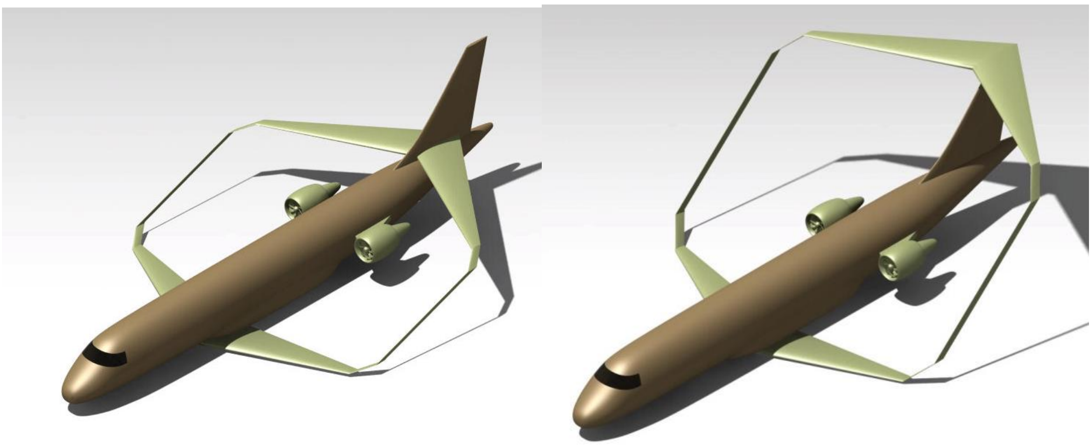


Figure 4-6 Aspect Ratio 7.5, horizontal wing separation 18 metres and vertical wing separation 4 & 10 metres

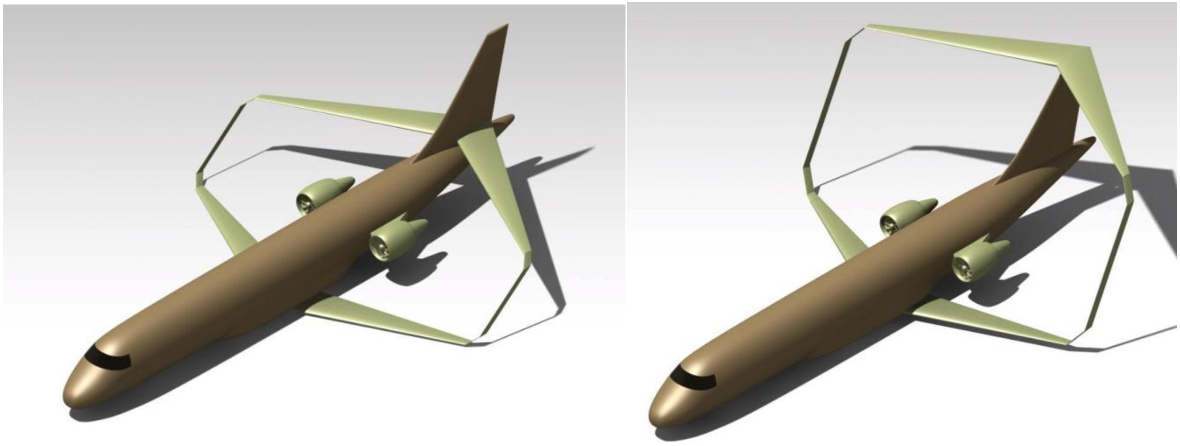


Figure 4-7 Aspect Ratio 11.5, horizontal wing separation 14 metres and vertical win separation 4 & 10 metres

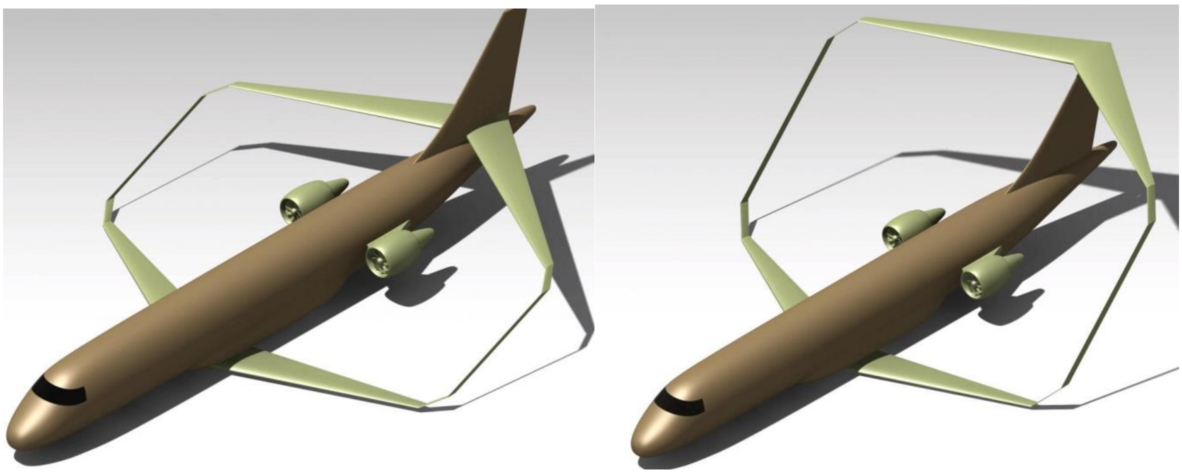


Figure 4-8 Aspect Ratio 11.5, horizontal wing separation 18 metres and vertical wing separation 4 & 10 metres

4.4.4 Non-Dimensionalised Values

For ease of visualisation and comparison, both the horizontal wing separation and the vertical wing separation were non-dimensionalised for these aircraft configurations by dividing the horizontal wing separation (D_h) by the length of the fuselage (l_f) and dividing the vertical wing separation (D_v) by the height of the fuselage plus vertical tail (h_{f+t}), respectively. This is illustrated in figures 4-9 and 4-10. Hence these values will be presented as a fraction during the results and analysis portion of the investigation.

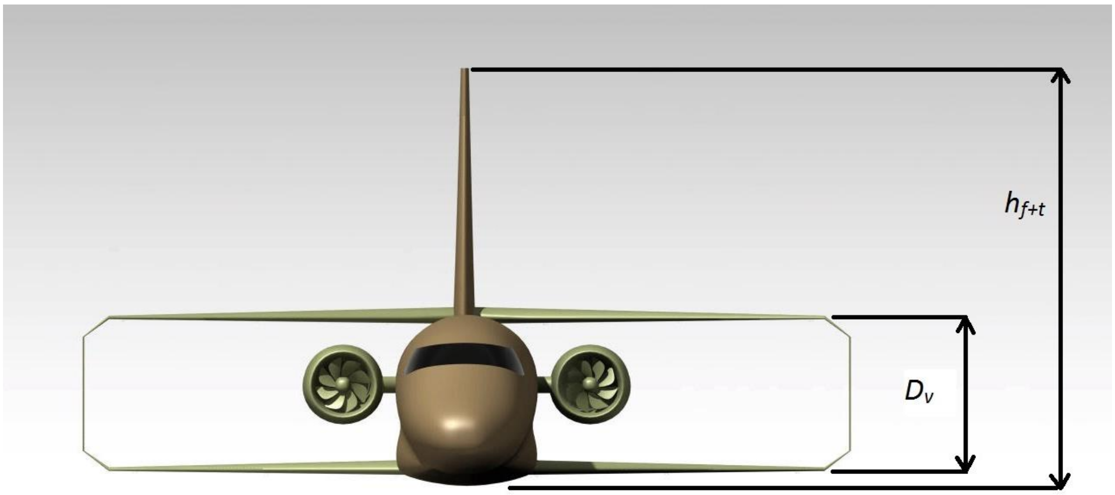


Figure 4-9 Non-dimensional vertical wing separation D_v/h_{f+t}

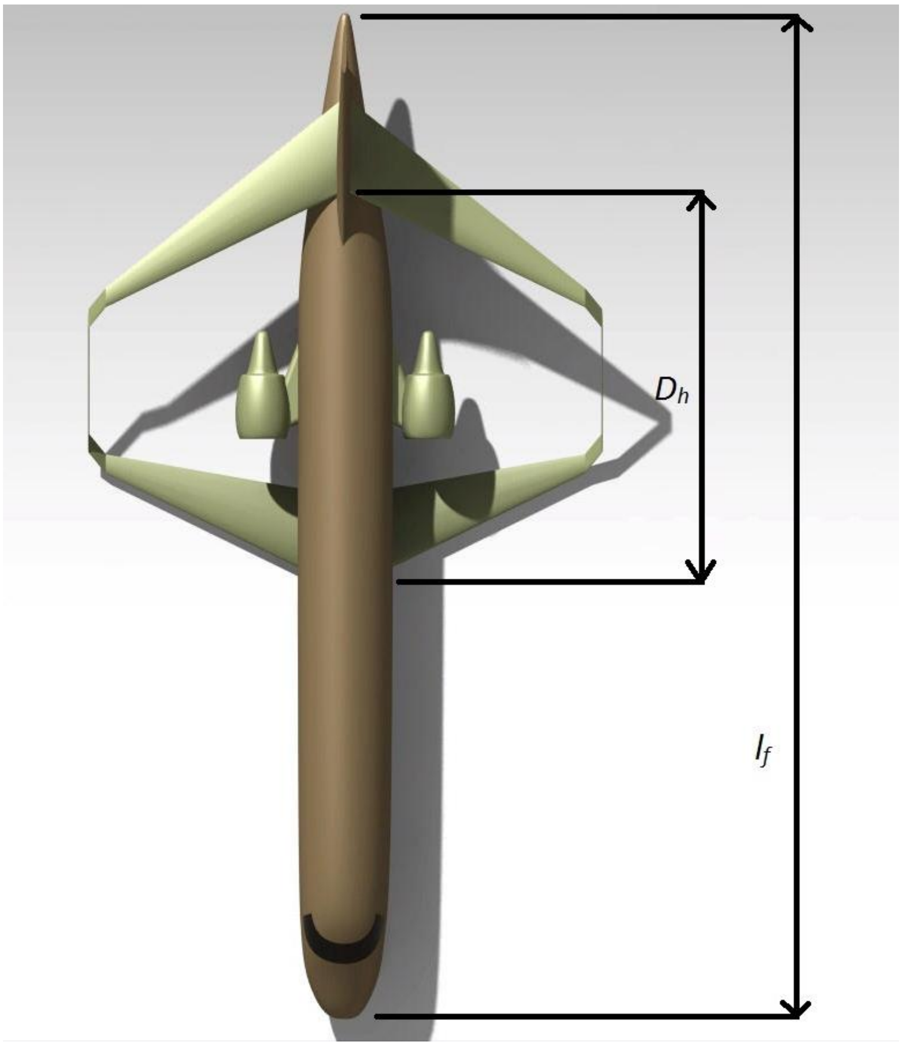


Figure 4-10 Non-dimensional horizontal wing separation D_h/l_f

4.5 Fuel Burn Analysis

The fuel burn analysis for the comparison between the conventional and box-wing aircraft was conducted using the Breguet range equation. The range equation evaluates the ideal range for the aircraft given the weights, velocity, specific fuel consumption and the lift-to-drag efficiency during the cruise phase of the mission as per Eq. 8 presented in the previous chapter.

However, in this case the range was specified, and the difference in the initial and final weights was the fuel burned during the cruise phase of that mission for that particular range as specified by the given mission parameters. Hence the equation could be rewritten as:

$$\log \frac{W_{initial}}{W_{final}} = \frac{R_{CR}}{\frac{V_{CR}}{C_T}\left(\frac{L}{D}\right)_{CR}} \tag{27}$$

The values for the analysis necessary here were then implemented from the aerodynamic and structural optimisation analyses that were the outputs of the toolchain. The lift-to-drag efficiency of the aircraft was calculated from the aerodynamic module, with the zero-lift drag analysis integrated from the build-up method. The initial weight of the aircraft was approximated as the maximum take-off weight, with the structural optimisation results integrated into the recalculated weights of the wings and the fuel weights. The cruise speed and the specific fuel consumption of the aircraft were known from the mission parameters and engine, respectively. Hence the final weight of the aircraft at the end of the cruise phase could be calculated by rearranging the equation above and solving for the final weight of the aircraft:

$$W_{final} = \frac{W_{initial}}{e^{\frac{R_{CR}}{\frac{V_{CR}}{C_T}\left(\frac{L}{D}\right)_{CR}}}} \tag{28}$$

Then the weight of the fuel used became the difference between the initial and final weights of the aircraft over the cruise phase of the flight:

$$\mathbf{W_{fuel}} = \mathbf{W_{initial}} - \mathbf{W_{final}} \quad \textbf{(29)}$$

Thus, the fuel burn from each of the configurations over the different missions could be analysed and compared using these equations.

4.6 Error Estimation and Validation

Error estimation analysis was already conducted for parts of the toolchain, with the WingMASS structural tool found to be accurate to within approximately 1% of a real aircraft wings' structural weight (Dorbath, 2014), while AVL has been analysed by several studies that have found it to be accurate to within 7% (Pereira, 2010) for coefficient of lift and induced drag analysis. The comparisons with real-world aircraft are only available for the conventional cantilever configurations, of course.

Validation of the toolchain and methodology described in this chapter, utilising the theories and tools from the previous chapter, was carried out by conducting the analysis for an Airbus A320 aircraft. The mission parameters of the A320 were used to design a conventional aircraft, which was then optimised both aerodynamically and structurally before undergoing the fuel burn analysis, hence covering the whole toolchain. The resulting fuel burn estimate for the aircraft designed to be equivalent to the A320 was found to be within 10% of the real aircraft's value as per available data, with the difference largely attributable to the focus of the design being on the cruise phase of the mission and the loads experience during that phase alone.

The relative crudity of the model is offset by the fact that the box-wing configurations analysed are not being compared to actual, real-world aircraft which have gone through a thorough detailed design process or analysis, but relative to conventional aircraft designed by the same process for the same mission. The results are hence always presented as relative to the conventional baseline aircraft for each mission, and the focus is on the relative savings offered by the change in configuration as opposed to any absolute comparison to real-world aircraft. This is a relatively common approach taken for unconventional conceptual design where the preponderance of unknowns and inability to calibrate tools and methods to actual aircraft mean that trends and relative differences are used to measure the improvements offered by the unconventional configuration.

5. Results

The results for the four different missions will be presented first, with some discussion of the trends and analysis, but a comprehensive and in-depth discussion of all of them together will be presented at the end so they can be compared and dissected in a meaningful manner.

The single parameter results (i.e. the change in fuel burn from the change in horizontal separation) are presented in a manner where a single parameter is varied while the other two are held constant. This is shown as a representation of the overall trend in the analysis, and should not be considered to be the only set of parameters investigated. Each combination of aspect ratio, horizontal wing separation and vertical wing separation was investigated, meaning that 80 different configurations were analysed for each mission. The combined results are presented when necessary. The singular values of the minimal horizontal separation, the maximum vertical separation and the median aspect ratio are chosen as representative of the possible optimal values for those individual geometric parameters.

For the following figures of results, F/F_c is the fuel burn by the box-wing configuration (F) as compared to the fuel burn by the conventional configuration (F_c) designed for the same mission. D_h refers to the horizontal separation between the wings, D_v to the vertical separation between the wings, l_f to the length of the fuselage and h_{f+t} to the height of the fuselage and tailplane combined.

5.1 Mission 1

The first scenario chosen for investigation covered the following parameters:

- 200 PAX
- 2000 Nm
- 0.78 cruise Mach no.
- 10,000 m cruise altitude

5.1.1 Horizontal Wing Separation

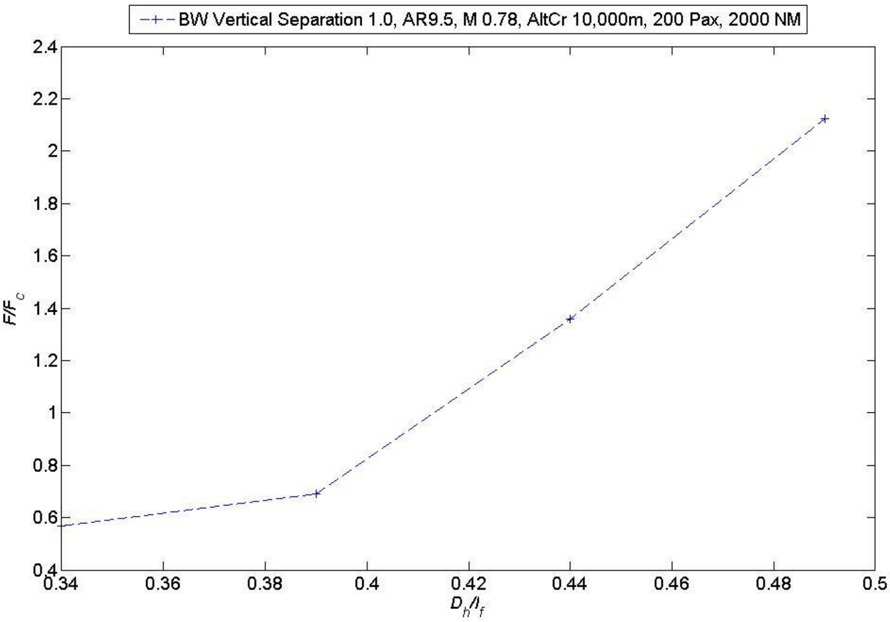


Figure 5-1 Fuel burn versus horizontal wing separation for Mission 1

5.1.2 Vertical Wing Separation

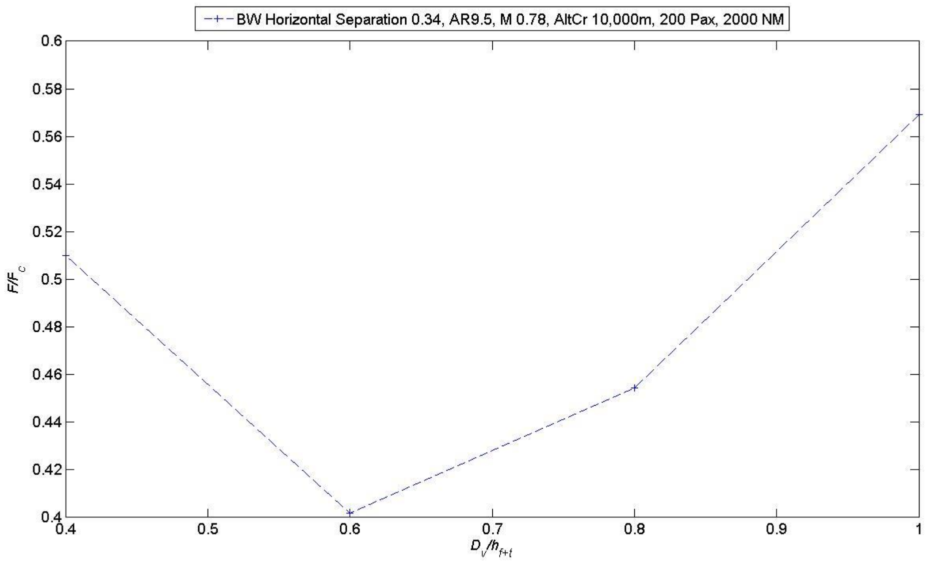


Figure 5-2 Fuel burn versus vertical wing separation for Mission 1

5.1.3 Aspect Ratio Variation

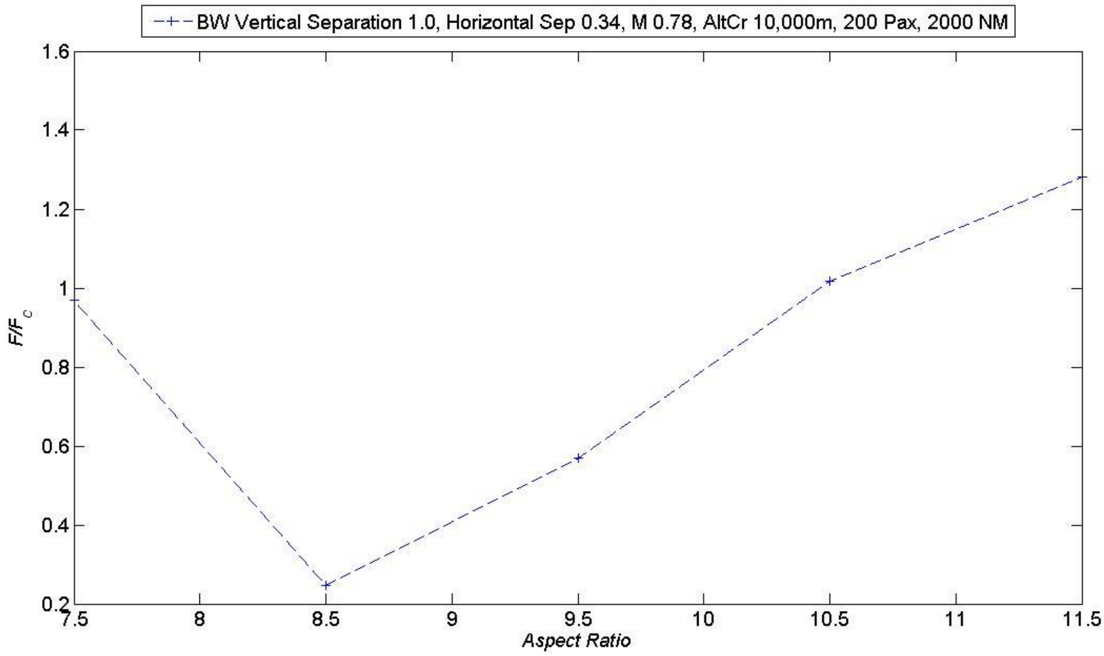


Figure 5-3 Fuel burn versus aspect ratio for Mission 1

For the first mission, the ideal D_h is the lowest one in terms of reducing fuel burn at 0.34, while optimal D_v is at 0.6 and the aspect ratio is 8.5. Indeed upon further investigation it was found the horizontal wing separation being optimal at its lowest value held true for all combinations of aspect ratio and vertical wing separation, meaning that the design space could be explored to find the most efficient combination of aspect ratio and vertical wing separation while holding the horizontal wing separation at the minimum value. It is important to note that the aspect ratio effect has a larger influence on fuel burn than the vertical wing separation, and this will be explored in more depth in the next chapter.

5.1.4 Aspect Ratio and Vertical Wing Separation

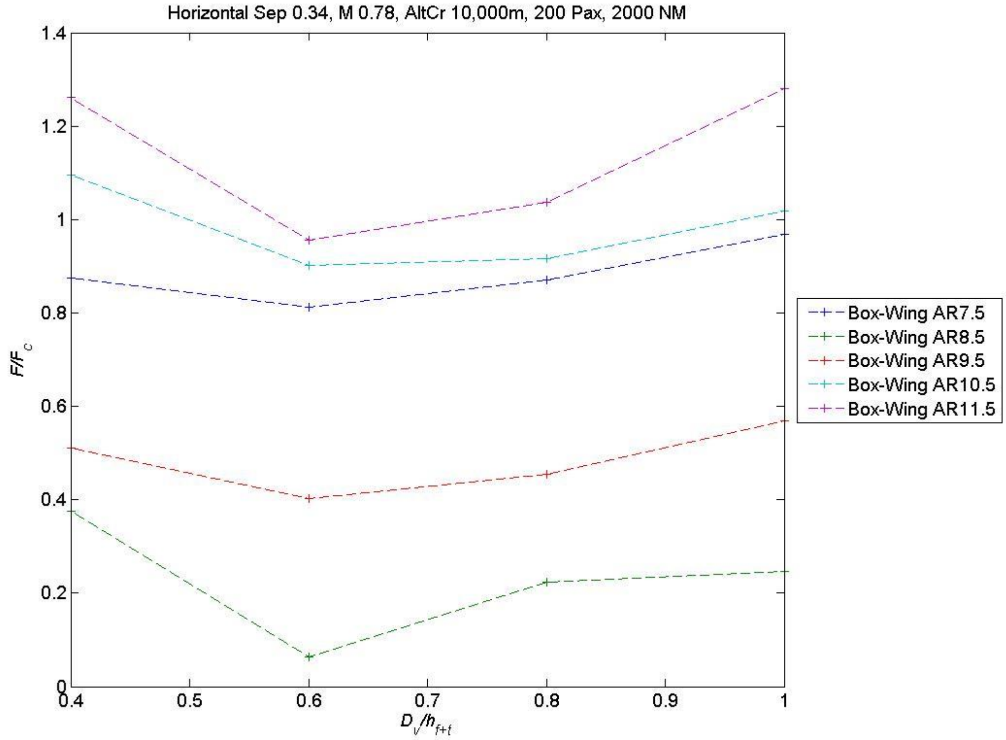


Figure 5-4 Fuel burn versus aspect ratio and vertical wing separation for Mission 1

For this mission the ideal combination of values for D_v of 0.6 and aspect ratio of 8.5 continued to hold true when exploring the combination of these parameters for all the values investigated. In terms of the fuel burn for the box-wing, for this particular mission no saving was calculated even with the most optimal combination of configurations, but the broader trends of the higher aspect ratio and vertical wing separation leading to more fuel burn were observed.

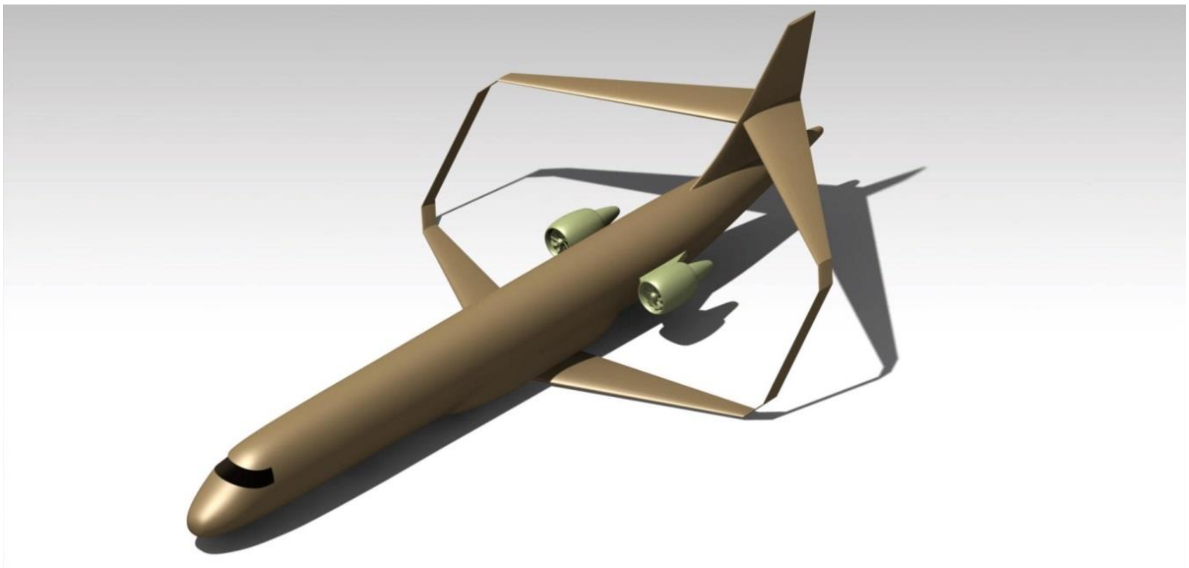


Figure 5-5 Optimal box-wing geometry for Mission 1, AR = 8.5, $\mathrm{D_v}$ = 0.6, and $\mathrm{D_h}$= 0.34

This optimisation from the aerostructural analysis clearly presents an aircraft configuration that will need to be modified for weight and balance issues. However, the horizontal wing separation has a small impact, and can be used to modify the configuration in line with this consideration. This will be addressed in greater detail in Section 7.2 of Chapter 7.

5.2 Mission 2

The second scenario chosen for investigation covered the following parameters:

- 150 PAX
- 1000 Nm
- 0.7 cruise Mach no.
- 5,000 m cruise altitude

5.2.1 Horizontal Wing Separation

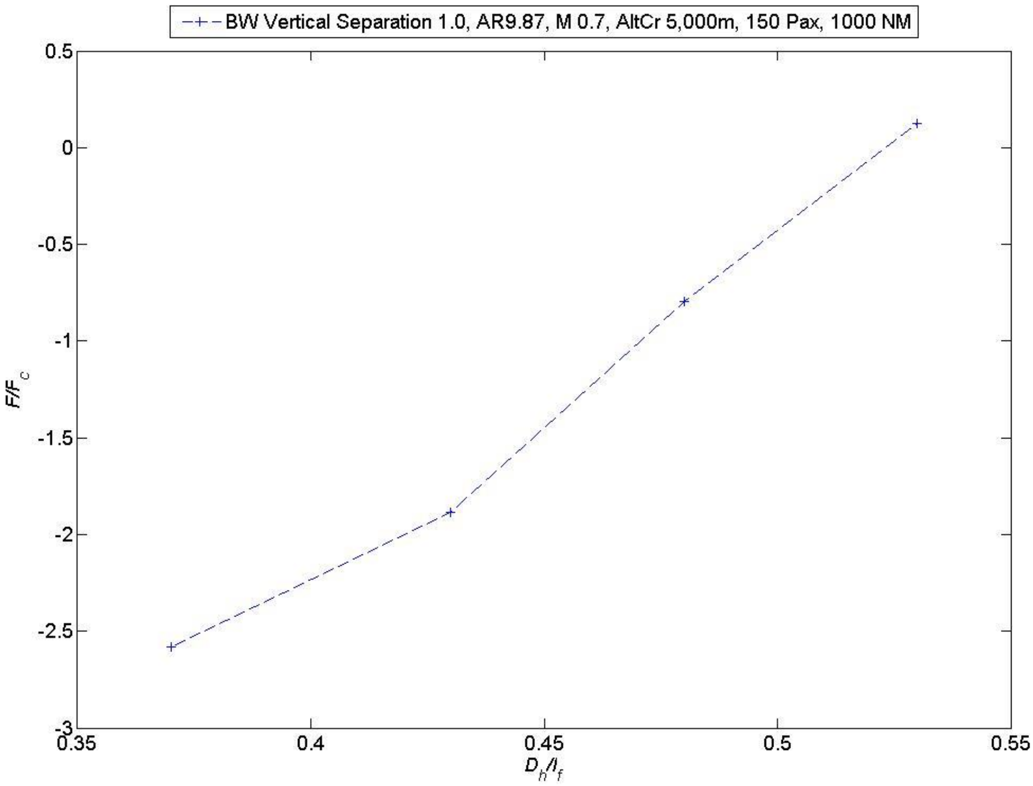


Figure 5-6 Fuel burn versus horizontal wing separation for Mission 2

5.2.2 Vertical Wing Separation

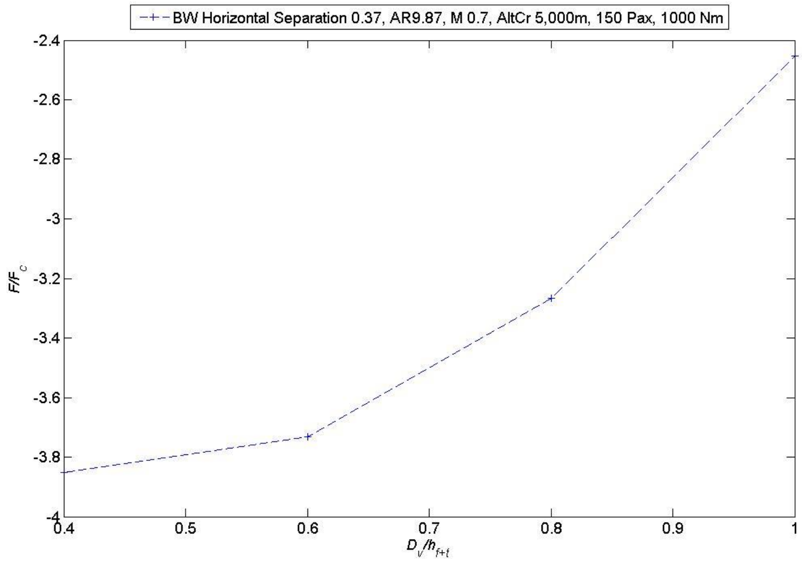


Figure 5-7 Fuel burn versus vertical wing separation for Mission 2

5.2.3 Aspect Ratio Variation

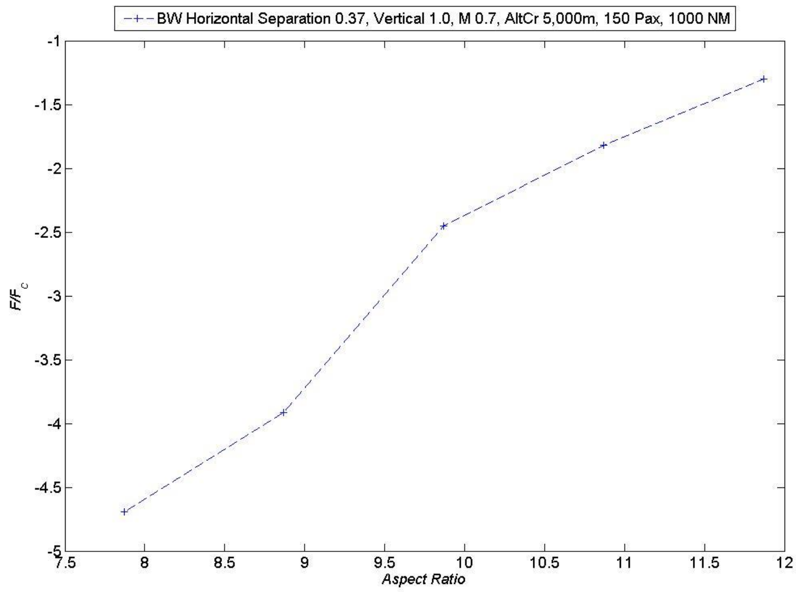


Figure 5-8 Fuel burn versus aspect ratio for Mission 2

The second mission showed a different set of results and trends for a very different set of parameters when compared to the first. This was for a much smaller, slower aircraft flying over a shorter distance at a lower altitude. In this case the D_h is also optimal at the minimum value of 0.37 (the fuselage is slightly smaller due to the lower number of the passengers for the payload) but the D_v is optimal at the lowest value of 0.4 and the aspect ratio is optimal at the lowest value of 7.87. Again the design space that combined the vertical wing separation and aspect ratio could be explored to see the interaction of the two and allow for the choice of the best configuration.

5.2.4 Aspect Ratio and Vertical Wing Separation

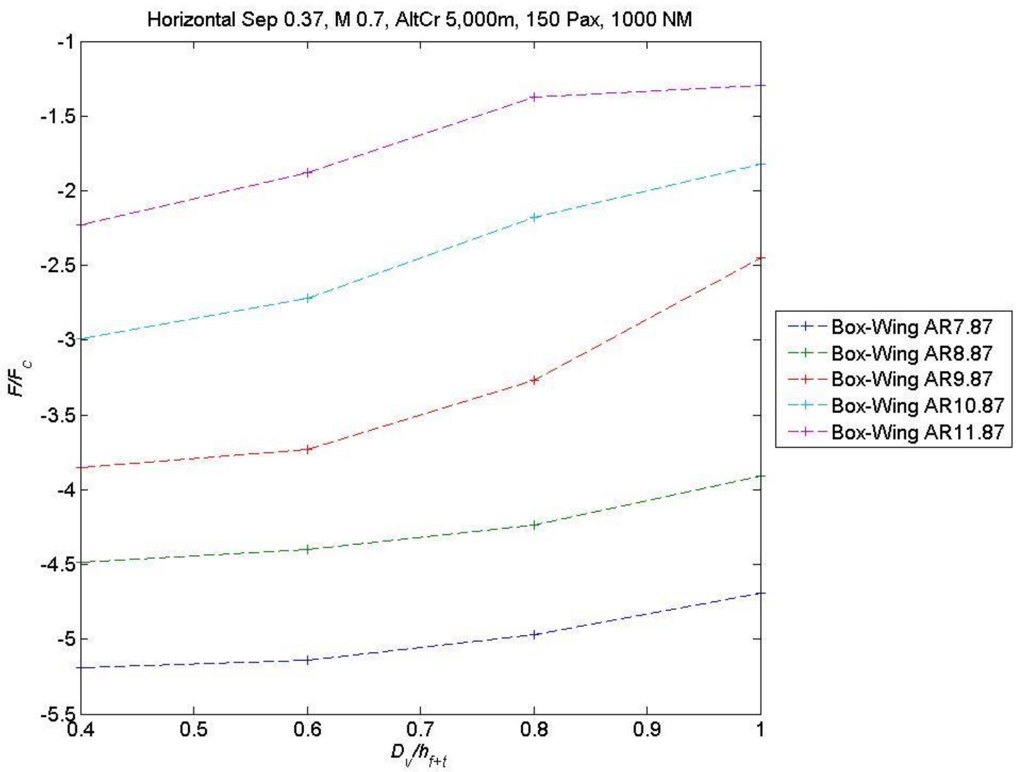


Figure 5-9 Fuel burn versus aspect ratio and vertical wing separation for Mission 2

In this case the minimum values of aspect ratio and vertical wing separation do lead to the lowest fuel burn, offering a reduction of over 5% compared the conventional configuration for this mission. The structural advantages offered by the lowest values of aspect ratio and vertical wing separation outweighed the aerodynamic advantages of higher values of those two parameters for this particular set of requirements, which is analysed further in Chapter 6.

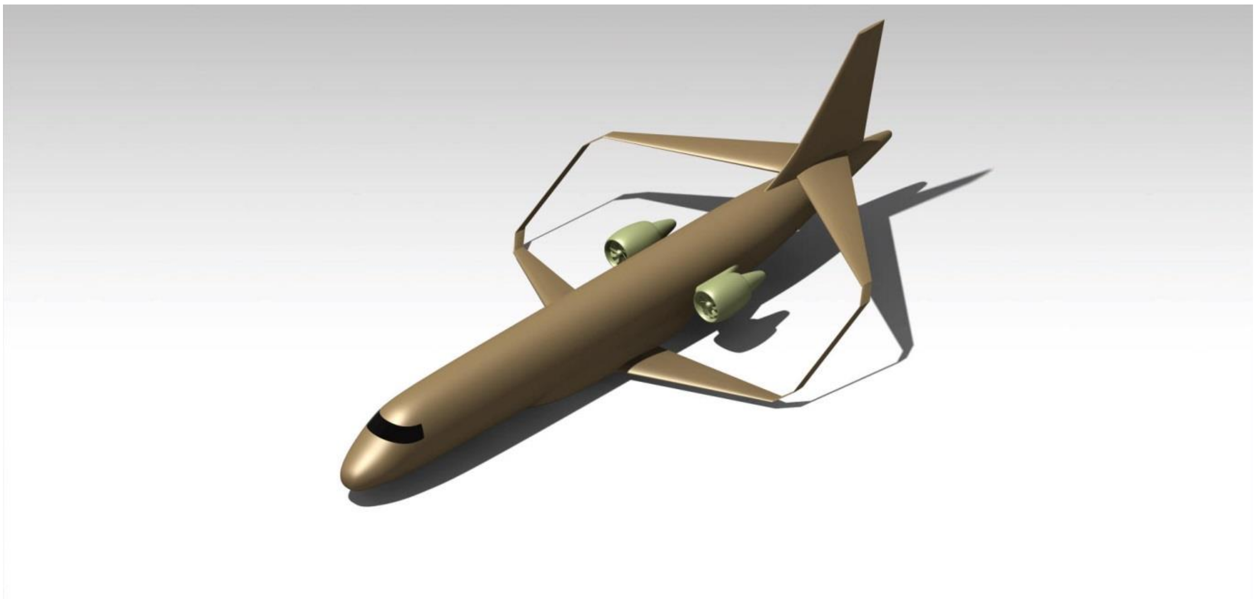


Figure 5-10 Optimal box-wing geometry for Mission 2, with AR = 7.87$\mathbf{D_v}$ = 0.4, $\mathbf{D_h}$ = 0.37

5.3 Mission 3

The third scenario chosen for investigation covered the following parameters:

- 175 PAX
- 1500 Nm
- 0.75 cruise Mach no.
- 7,500 m cruise altitude

5.3.1 Horizontal Wing Separation

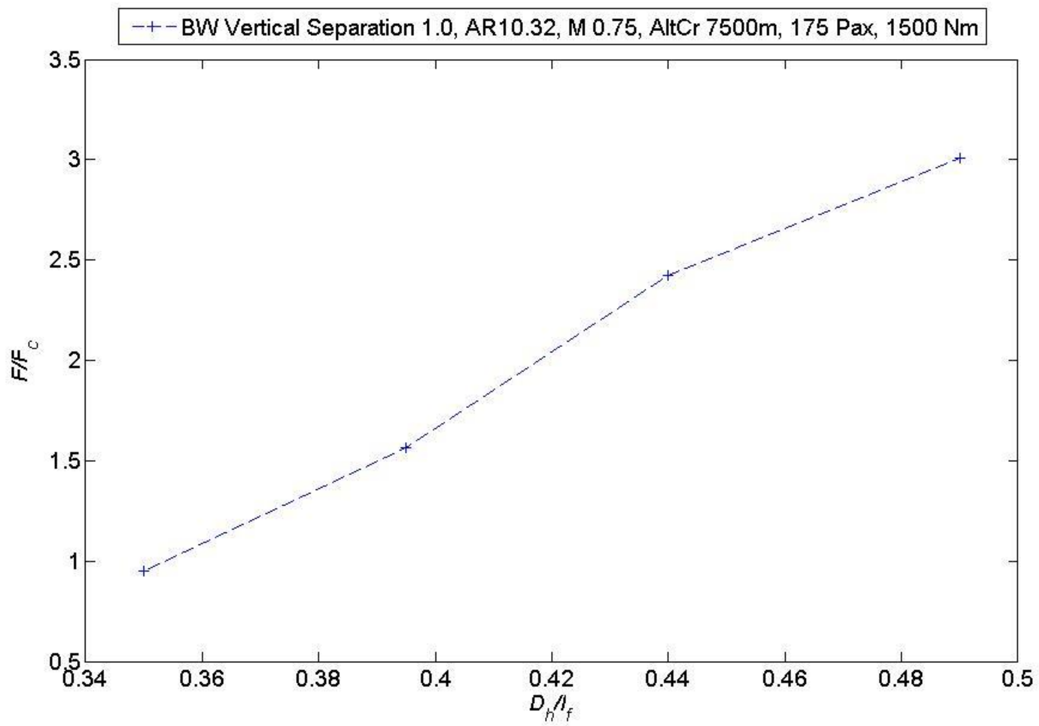


Figure 5-11 Fuel burn versus horizontal wing separation for Mission 3

5.3.2 Vertical Wing Separation

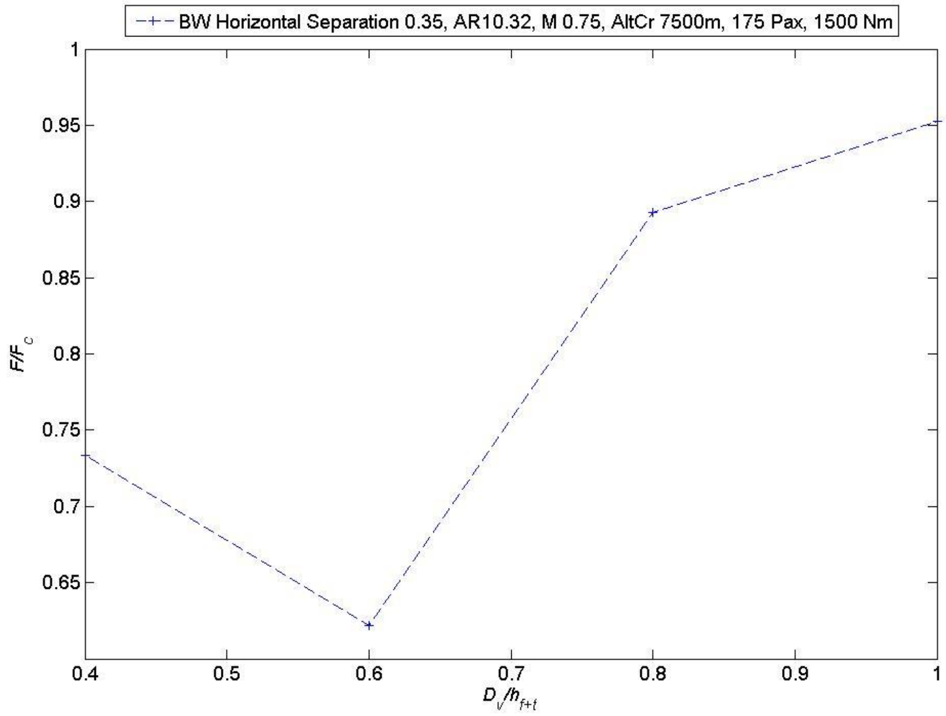


Figure 5-12 Fuel burn versus vertical wing separation for Mission 3

5.3.3 Aspect Ratio Variation

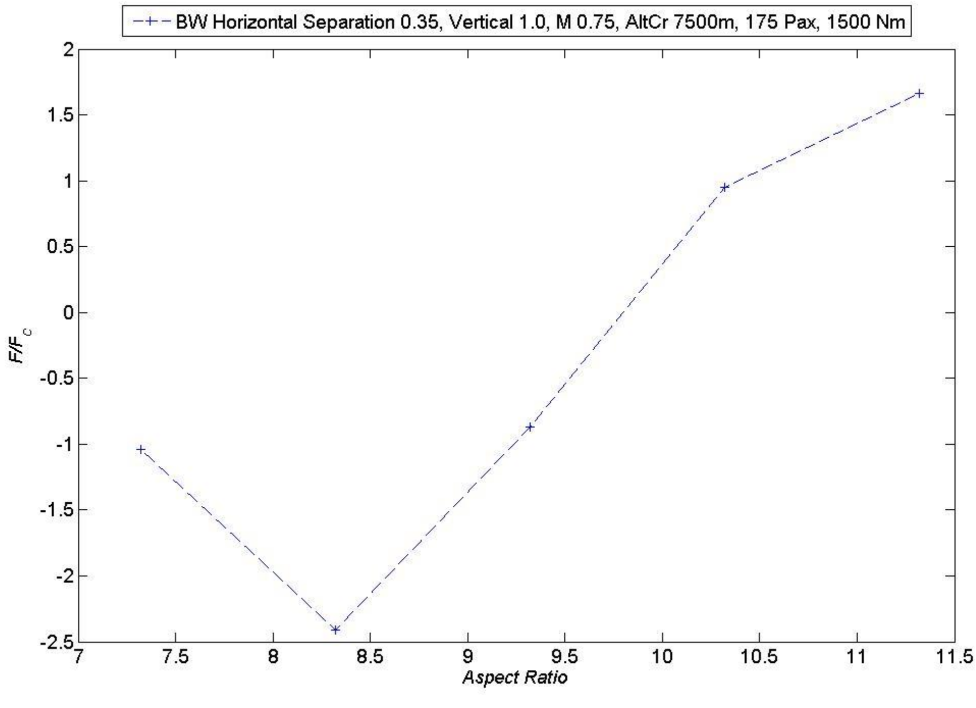


Figure 5-13 Fuel burn versus aspect ratio for Mission 3

For Mission 3, the D_h is optimal at the lowest value of 0.35 again, with the D_v and aspect ratio being optimal at low but not minimal values of 0.6 and 8.32 respectively. The trends and interactions of the vertical wing separation and aspect ratio are again worth exploring for this set of mission requirements.

5.3.4 Aspect Ratio and Vertical Wing Separation

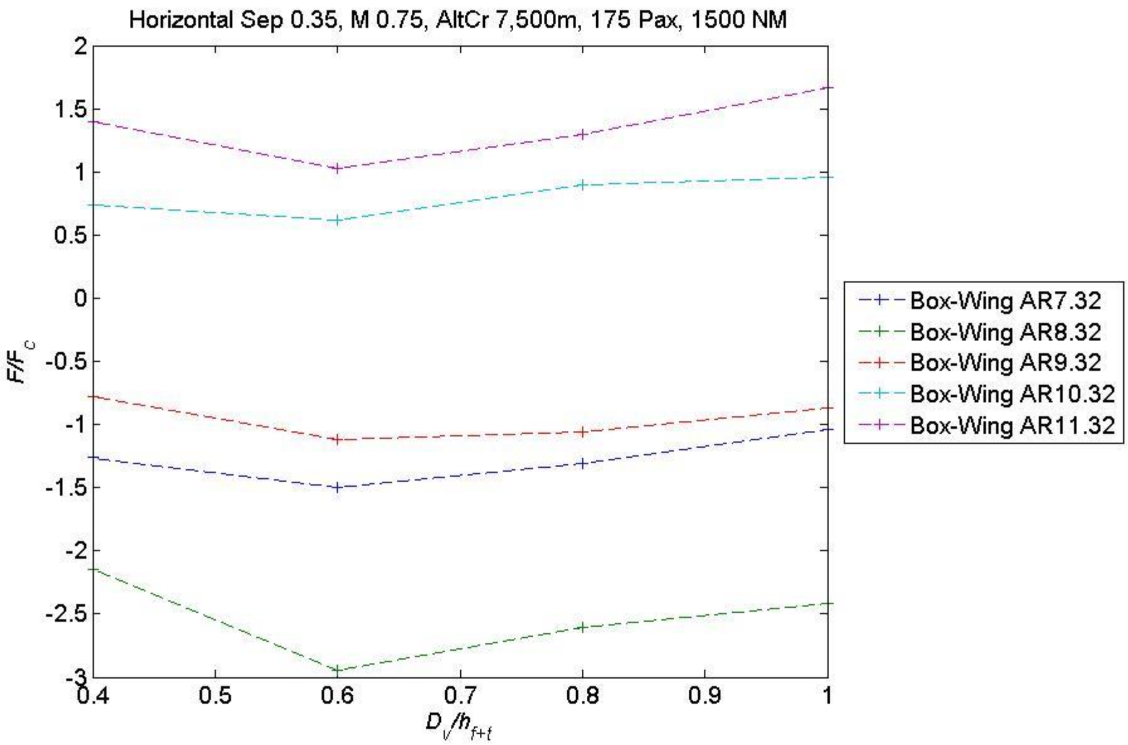


Figure 5-14 Fuel burn versus aspect ratio and vertical wing separation for Mission 3

Here again it is clear that the optimal solution in terms of geometric parameters occurs for the aspect ratio of 8.32 with a D_v of 0.6 at the D_h of 0.35. There is a fuel burn saving here of just under 3% for the box-wing over the conventional configuration, which is not as large as the saving for the Mission 2 but still significant in its own right. It is clear that for missions with shorter ranges and lower cruise speeds, the box-wing starts becoming a more attractive proposition. This will be analysed further in Chapter 7.

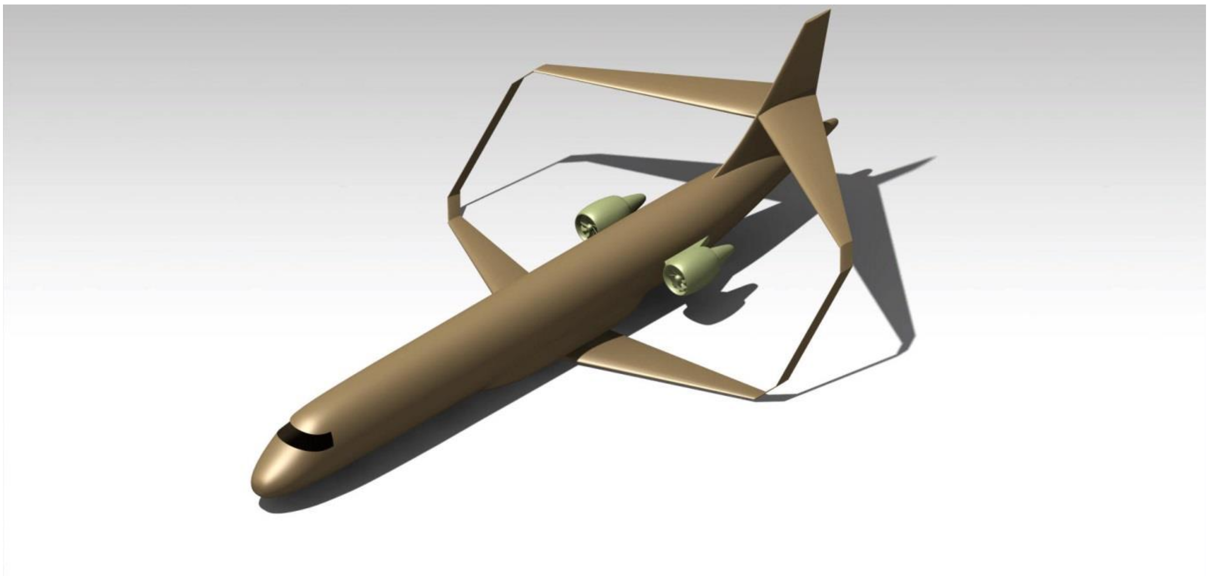


Figure 5-15 Optimal box-wing geometry for Mission 3 with AR = 8.32, D_v = 0.6, D_h = 0.35

5.4 Mission 4

The fourth scenario chosen for investigation covered the following parameters:

- 200 PAX
- 1000 Nm
- 0.73 cruise Mach no.
- 7,500 m cruise altitude

5.4.1 Horizontal Wing Separation

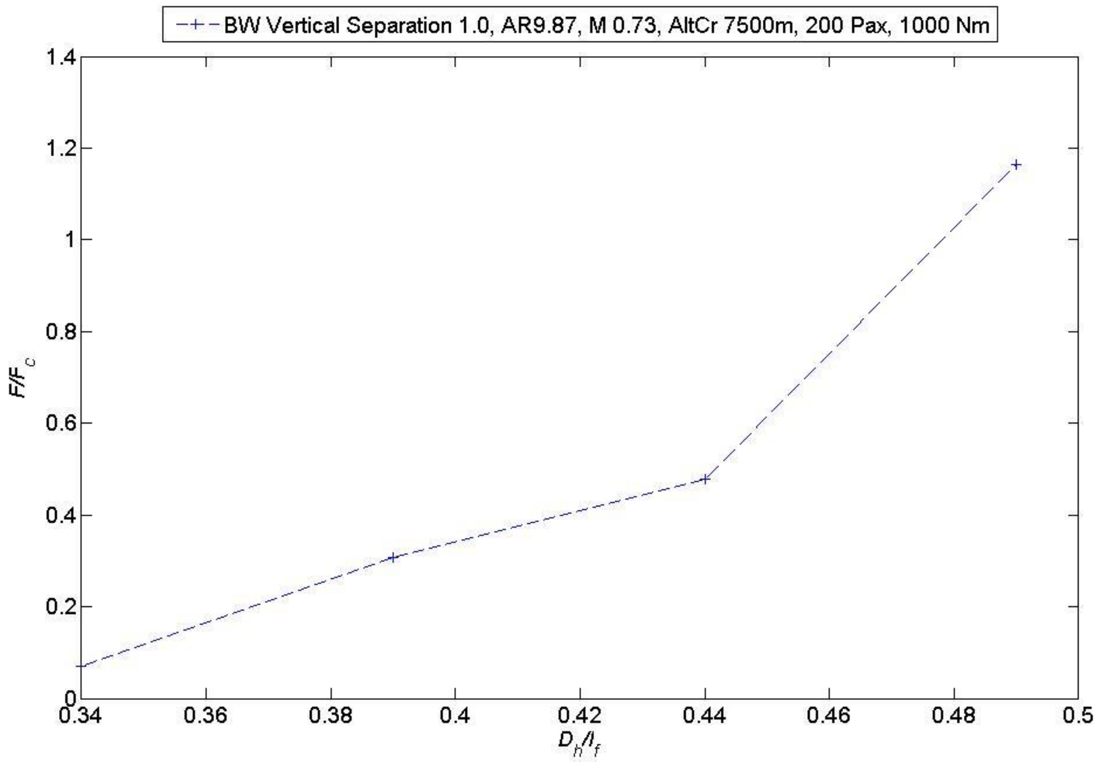


Figure 5-16 Fuel burn versus horizontal wing separation for Mission 4

5.4.2 Vertical Wing Separation

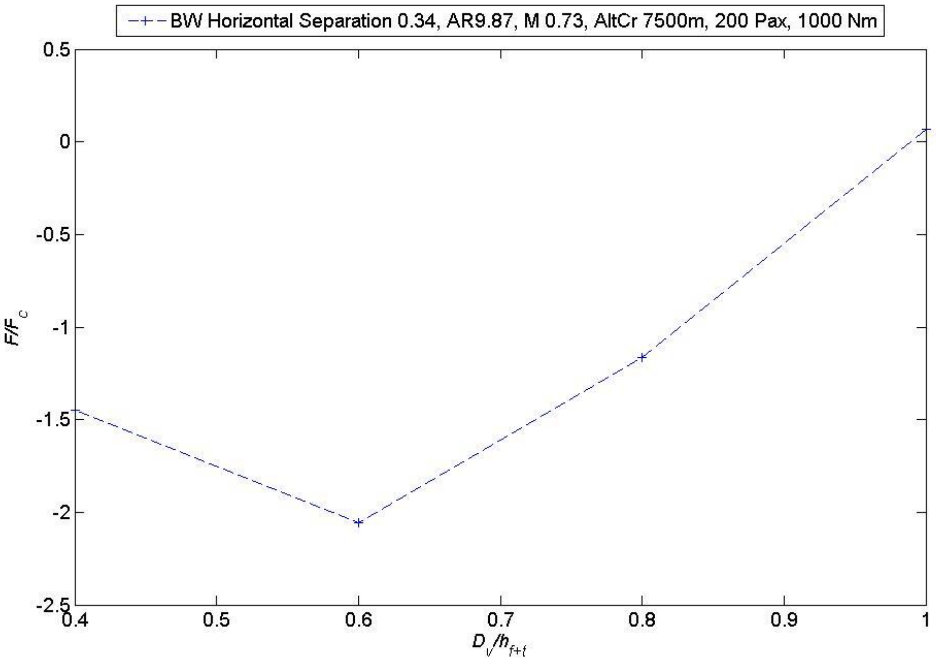


Figure 5-17 Fuel burn versus vertical wing separation for Mission 4

5.4.3 Aspect Ratio Variation

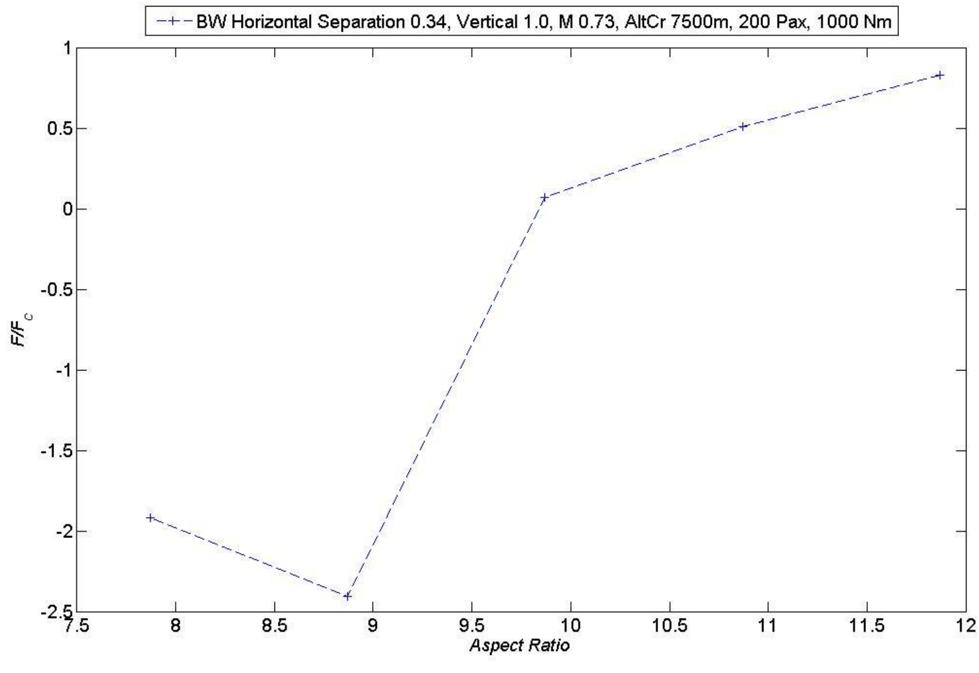


Figure 5-18 Fuel burn versus aspect ratio for Mission 4

For Mission 4 the D_h was again optimal at the minimum value of 0.34, while the optimal D_v was 0.6 and the optimal aspect ratio was 8.87, falling into same or similar ranges as Missions 1 and 3. Combing the design space of the two geometric parameters, the aspect ratio and the vertical wing separation, was once again important to find the optimal point which would lead to the lowest fuel burn.

5.4.4 Aspect Ratio and Vertical Wing Separation

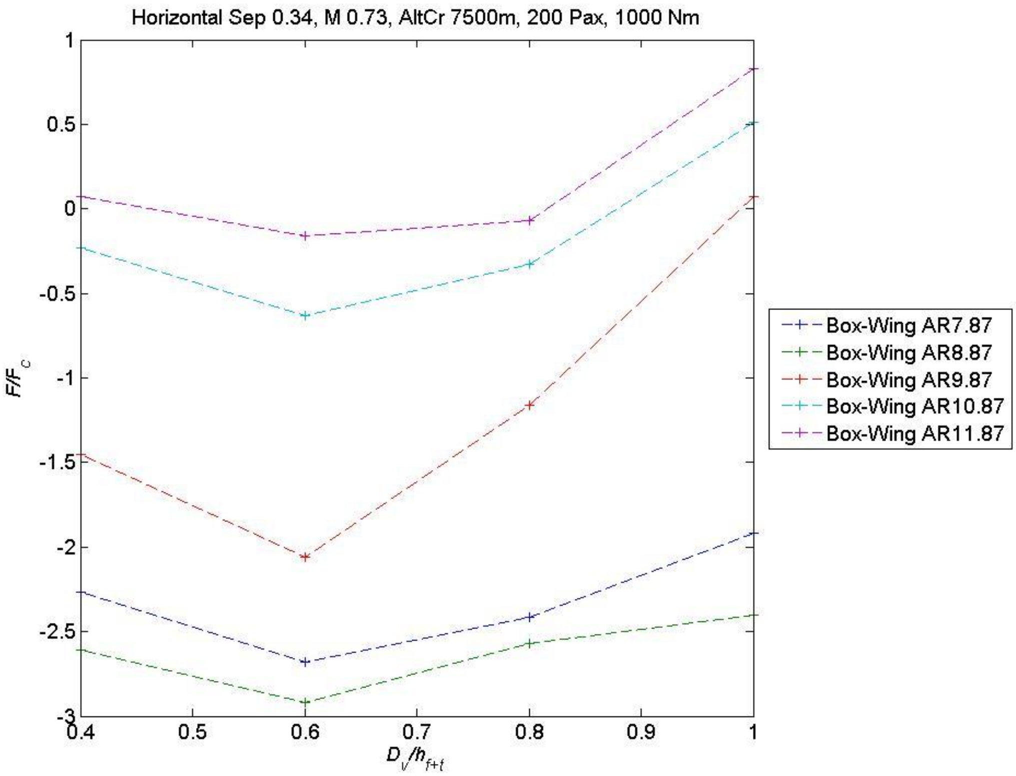


Figure 5-19 Fuel burn versus aspect ratio and vertical separation for Mission 4

Again, the optimal combination of aspect ratio and vertical wing separation leads to the lowest fuel burn for the box-wing as compared to the conventional design for this particular set of mission requirements. In this case, a projected saving of just under 3% is possible. Since Mission 4 combined a larger passenger payload over shorter distances, this reduction in fuel burn offers an intriguing possibility for future designers, and shows how trading off certain requirements against each other can lead to the kind of design space and optimal point where the fuel burn is reduced for a box-wing over the conventional configuration.

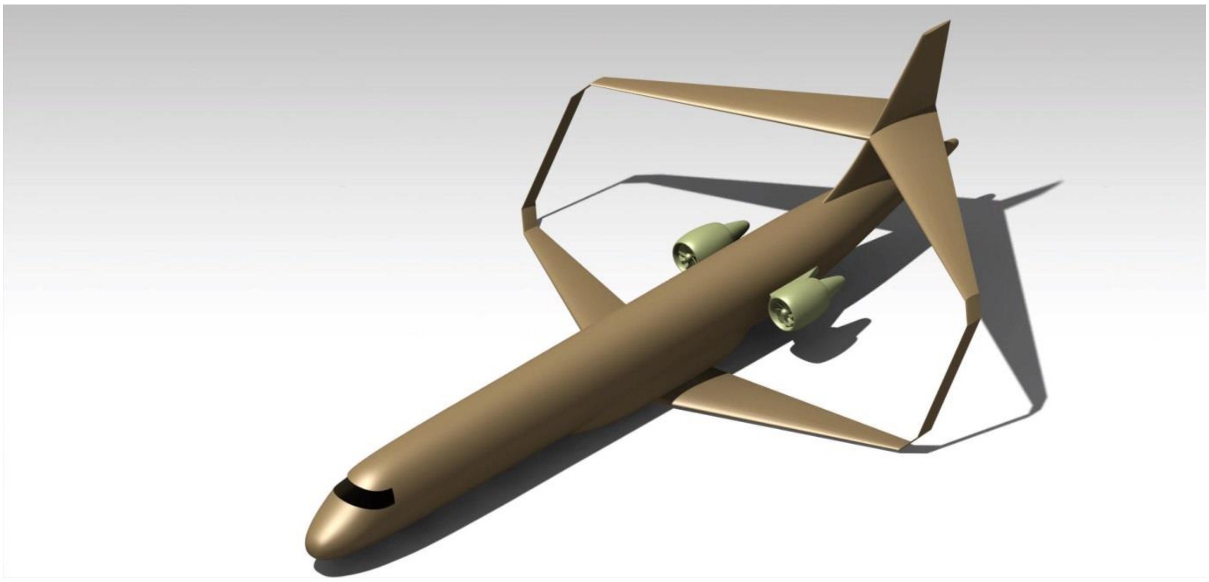


Figure 5-20 Optimal box-wing geometry for Mission 4 with AR = 8.87, $\mathrm{D_v}$ = 0.6 and $\mathrm{D_h}$ = 0.34

6. Analysis and Discussion of Parametric Variation

6.1 Horizontal Wing Separation

The results show that the horizontal wing separation has a small negative influence on fuel consumption for all missions as per Figures 5-1, 5-6, 5-11 and 5-16 presented in Chapter 5. It is best, independent of the mission, to minimise the horizontal wing separation as much as possible, because the trend of the increasing fuel consumption with increasing horizontal wing separation is constant through all the missions analysed. However, other factors such as weight and balance, stability and manufacturing utility will likely play a part in determining exactly how much horizontal wing separation is required for a particular configuration. The following figures are all taken from Mission 1 to illustrate the principles at work.

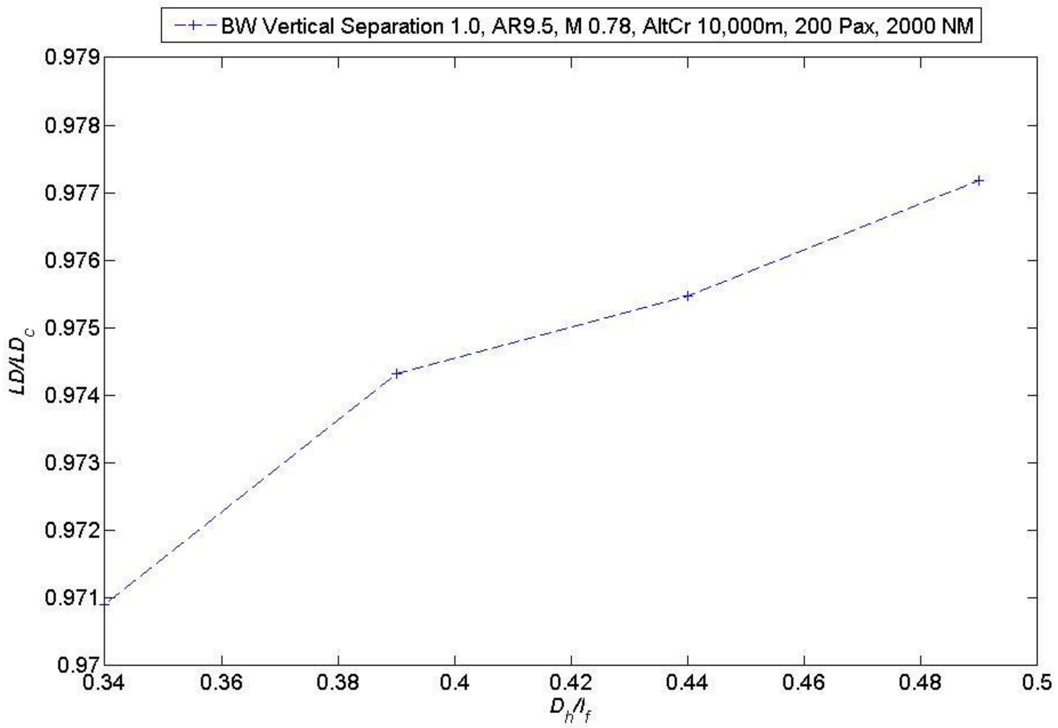


Figure 6-1 Lift-to-drag performance versus horizontal wing separation for Mission 1

It is shown in Figure 6-1 that the lift-to-drag performance of the box-wing configurations changes very minimally with horizontal wing separation. This slight improvement arises from the small decrease in the interference of the flows of the wings and the downwash on the rear wing. Since the rear wing is higher than the front wing, there is not as much effect on it than if the reverse configuration were used.

With the aerodynamic characteristics not changing significantly as the wing separation was increased, the structural efficiency of the wing becomes the more important factor with respect to the aerostructural design. Increased horizontal wing separation leads to increased loads, and the vertical wing has to elongate and become more diagonal, requiring more stiffness and strength to maintain its shape. This leads to heavier spars, ribs and skins in the wing primary structure, increasing the overall weight of the wing planform and hence of the aircraft itself. The increase in wing weight with horizontal wing separation, as shown in Figure 6-2, generally outstrips any improvement offered in terms of lift-to-drag ratio.

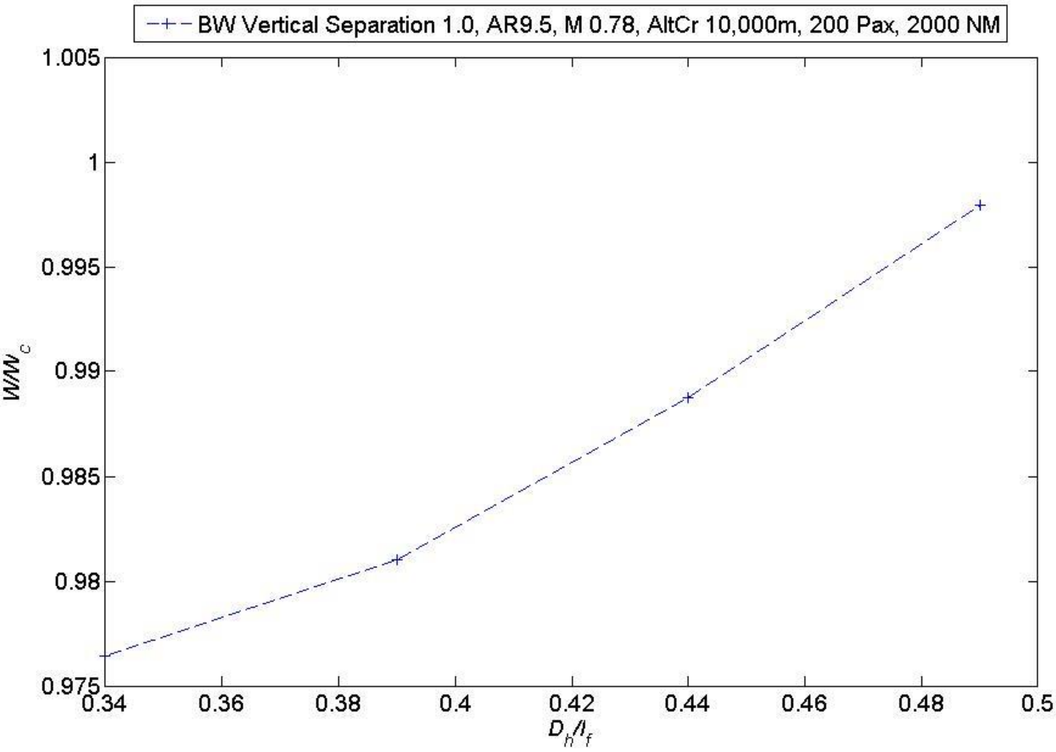


Figure 6-2 Aircraft take-off weight comparison versus horizontal wing separation for Mission 1

Hence when considering the design space exploration of the box-wing purely from an aerostructural perspective, keeping the horizontal wing separation to the minimum value for all missions while investigating the interlinked nature of the vertical wing separation and the aspect ratio is the most sensible course of action. Instead, the other parameters will become the focus of greater investigation as they offer increased scope of efficiency increase for the box-wing planform without the inherent performance disadvantage inherent to the increased horizontal wing separation between the wings.

6.2. Vertical Wing Separation

From the vertical wing separation parameter sweeps as per Figures 5-2, 5-12 and 5-17, for most of the missions the optimum vertical wing separation does not lie at either end of the spectrum but in the middle, at a point where both the aerodynamic and structural characteristics combine at the optimal design point to offer the best improvement in the performance for the box-wing over the conventional design.

The aerodynamic efficiency of the configuration increases with vertical wing separation, as was hypothesised by the theory and is well-understood, and shown in Figure 6-3. Furthermore, the lift-to-drag ratio of the configuration reduces only slightly as the vertical wing separation is reduced- most of the aerodynamic advantages of the box-wing from the reduction in induced drag and the airflow staying more attached still occurs at the lower values of vertical wing separation.

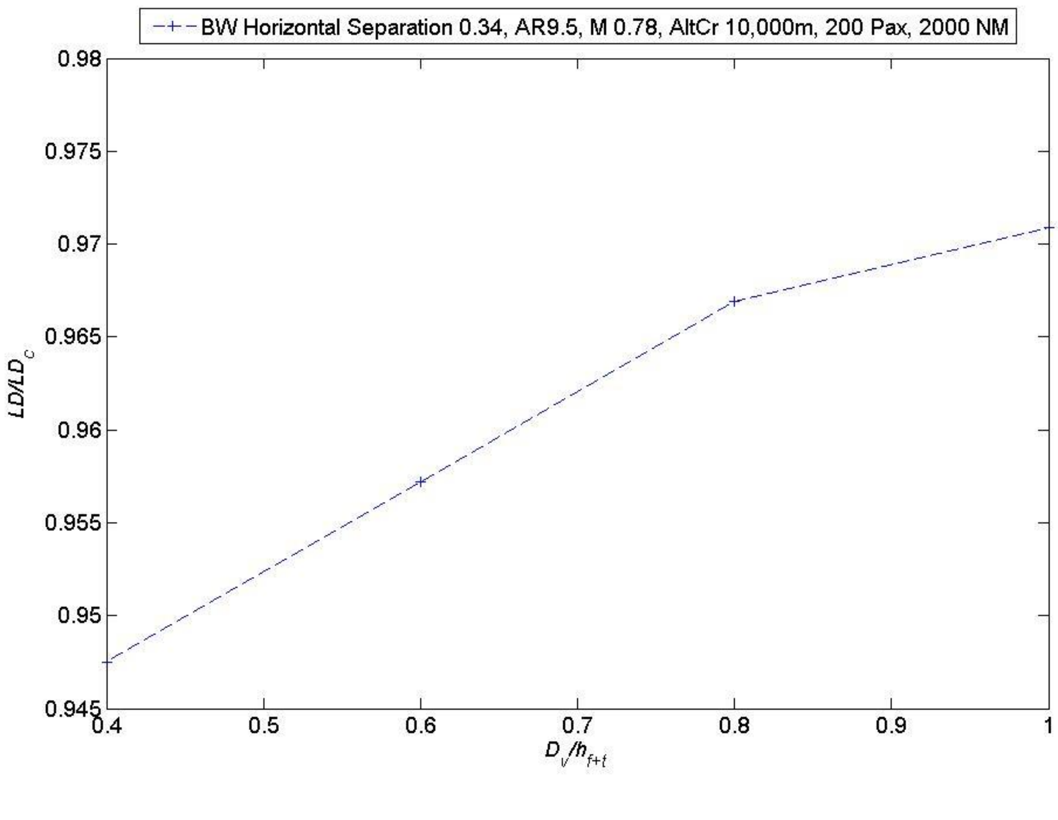


Figure 6-3 Lift-to-drag performance versus vertical wing separation for Mission 1

However, the structural efficiency of the box-wing planform improves as the vertical wing separation is lowered. This is due to the fact that the vertical wing is subjected to different loads, especially around the joints to the horizontal wings, and in terms of the magnitude of the butterfly-shaped load along the vertical wing. These additional loads arise from the twisting and torsion the vertical wing is subject to, as well as the greater buckling loads that must be resisted by this relatively slender structural member, as shown in Figs 6-5 to 6-8.

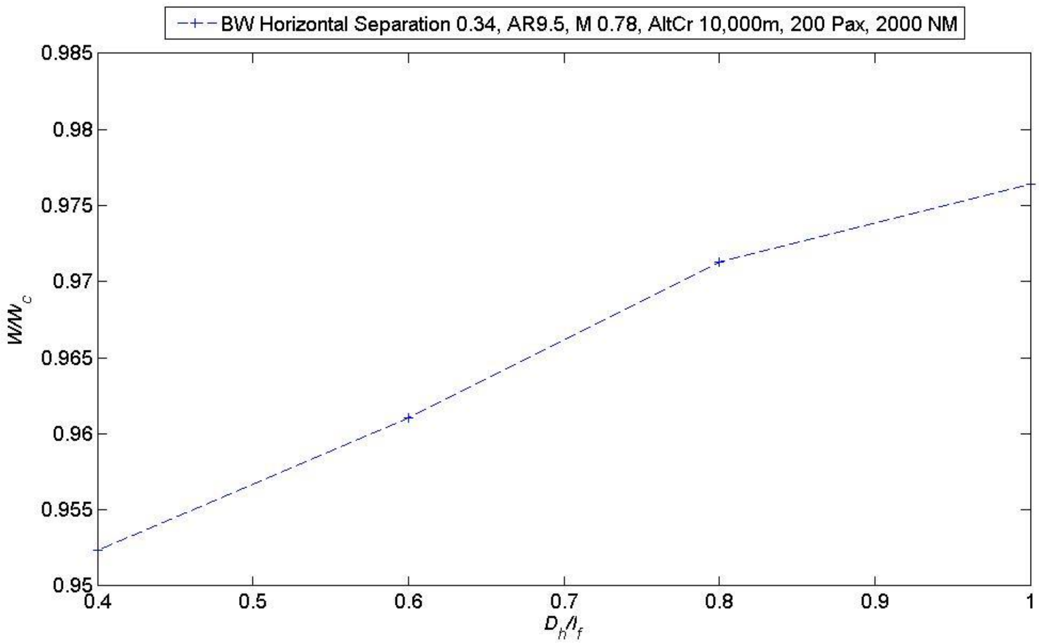


Figure 6-4 Aircraft take-off weight comparison versus vertical wing separation for Mission 1

Figure 6-5 Von Mises stresses for configuration with maximum vertical wing separation for Mission 1

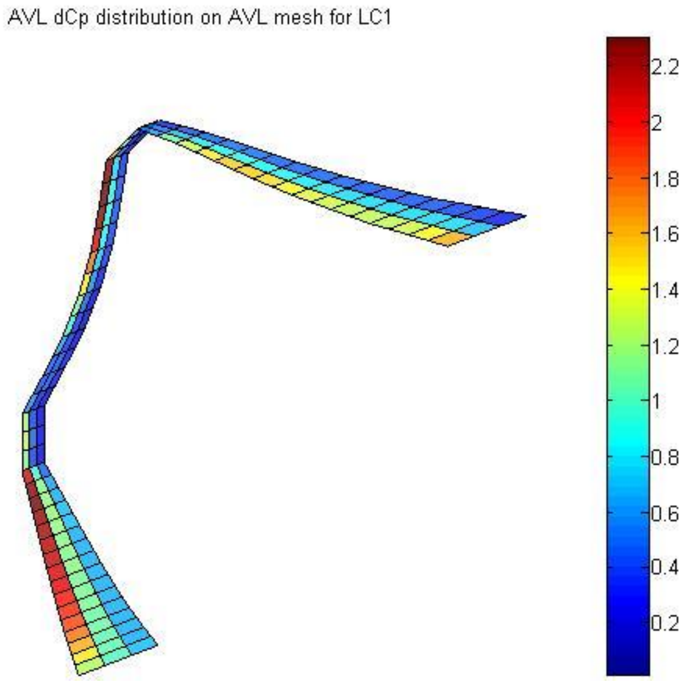


Figure 6-6 AVL pressure differential for configuration with maximum vertical wing separation for Mission 1

As can be seen in Figures 6-5 and 6-6 from the Von Mises stresses in ANSYS and the pressure differential mapped onto the AVL mesh, the larger vertical wing separation is leading to higher stresses and deflection, especially of the vertical wing when the vertical wing separation is at its highest value of 1 for a box-wing configuration, with the rear wing at the tip of the vertical tail.

In contrast, the Figures 6-7 and 6-8 show that for the same horizontal wing separation and aspect ratio for the same mission, a planform with the vertical wing separation of 0.6 shows significantly lower Von Mises stresses and pressure differential, with much less deflection and bending of the vertical wing especially. The pressure differential is critical as it illustrates the distribution of the greater loads and bending moments on the vertical wing, which much more structural support. The configuration with the maximum vertical wing separation had a critical Von Mises stress 13% higher than the configuration with the vertical wing separation of 0.6.

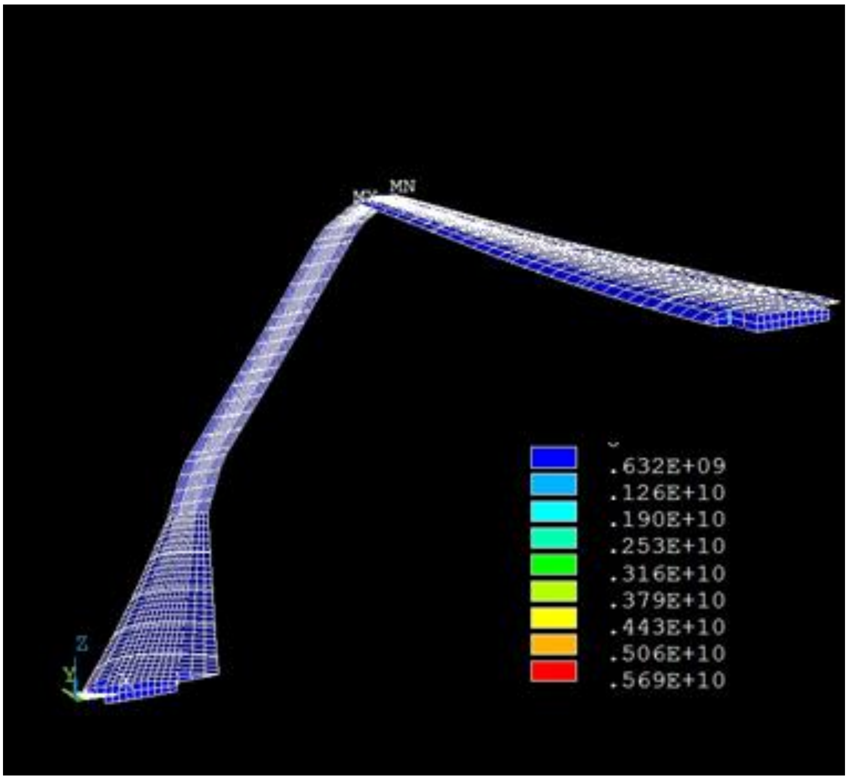


Figure 6-7 5 Von Mises stresses for configuration with vertical wing separation of 0.6 for Mission 1

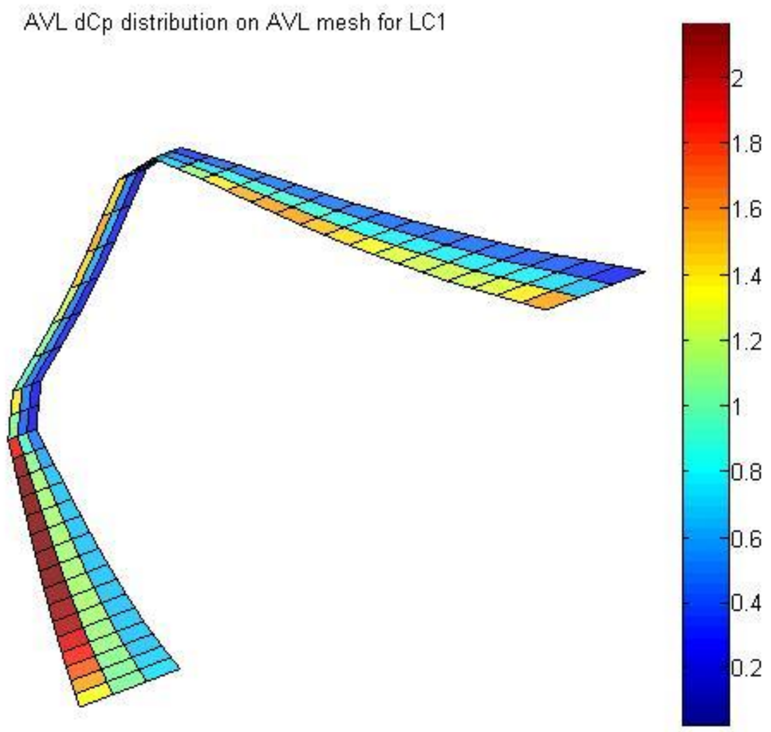


Figure 6-8 AVL pressure differential for configuration with vertical wing separation of 0.6 for Mission 1

This means greater structural support is required at the joints between the vertical horizontal wing, especially the upper wing, and those loads need to be supported and transferred over that wing too. Hence the upper wing has to be heavier and stronger to resist those loads and moments when the vertical wing separation is much greater.

This interaction of aerodynamic and structural factors is an important finding, as previous design studies have all focused on maximising the vertical wing separation of the two wings of the box-wing, focusing on the aerodynamic benefits only. However, the structural side of the problem has rarely been investigated at the same time. As can be seen, the optimum solution is generally not at either extremes of the range of values, but at a vertical wing separation that offers the best of both the aerodynamic and structural characteristics and efficiency of the box-wing configuration.

For most of the missions studied, the vertical wing separation is optimal at a value of 0.6 vertical wing separation between the wings. Hence the structural efficiency of the wing at lower values of vertical wing separation tends to dominate the overall fuel burn of the wing. At this value, the aerodynamic benefits of the configuration are sufficiently great in combination with the weight savings from the lower values of the vertical wing separation that the greatest improvement in fuel burn is seen for most missions. The only mission for which this is not true is Mission 2, shown in Figure 5-7, which has its minimum fuel burn when the vertical wing separation is as its lowest value of 0.4. This is due to the fact that this mission is being flown with the smallest payload at the lowest and slowest altitude and speed for the minimum range. The aircraft's aerodynamic efficiency matters the least in this case, and the structural efficiency dominates even more, meaning the absolute best case for lowest weight is also the best case in terms of fuel burn.

6.3. Aspect Ratio

The optimum aspect ratio for the box-wing configuration for three of the four mission scenarios is not one where the value is at the maximum or minimum, but one where the structural behaviour and aerodynamic behaviour combine to offer an advantage that is not readily discernible without the multidisciplinary analysis. This was shown in Figures 5-3, 5-13 and 5-18. Here the short, lower aspect ratio wings of the box-wing planform still perform well enough aerodynamically while offering a weight advantage over the equivalent conventional planform. On the other hand, the long, thin wings of the high-aspect ratio designs are necessarily much heavier to resist the bending, twisting and torsion loads that affect the wing planform and hence lose any aerodynamic advantage they gain by the necessary increased structural weight to resist those loads leading to an overall disadvantage when considering the fuel burn and performance of those configurations over the mission analysed.

This aspect ratio outcome is actually quite different and perhaps even counterintuitive when compared to other studies of the box-wing. Previous studies have often concentrated on comparing conventional planforms and their box-wing equivalents by leaving the wingspan of both planforms equal. This meant the box-wing had a far high aspect ratio on each wing, leading to increased aerodynamic performance at a great structural cost. However, the true upside to the box-wing may well lie in a planform that provides a structural benefit and weight saving over the conventional configuration while delivering an aerodynamic performance that is on par or close to the conventional. That is to say, it is not to vastly improve the aerodynamic performance but to keep that relatively steady while reducing the structural weight of the overall lifting area and hence lead to an improvement in fuel burn from a largely structural saving perspective as opposed to a massive reduction in drag. Conventional wings that were of lower aspect ratio and would provide similar weight savings would pay large penalties in terms of induced drag and decreased aerodynamic efficiency, but the inherent qualities of the box-wing counteract that for this configuration and allow for the structural improvement to be possible without the same aerodynamic disadvantages.

The only concept with a configuration that had an optimum aspect ratio at its lowest value was Mission 2 as shown in Figure 5-8. This outcome is similar to the outcome for the vertical wing separation where the optimal value was also the lowest for that parameter for this scenario. This is due to the fact that the mission requirements for this particular aircraft were the least demanding in terms of aerodynamic performance, and hence the structural considerations dominated the parameter sweep and the design space, leading to the optimal point occurring where the structural savings were maximised.

In terms of the value of the aspect ratio, generally a value around 7.9-8.9 is the most advantageous, depending on the mission. At this design point, the structural weight saving advantages of shorter, more structurally efficient wings combine with the aerodynamic advantage of the box wing configuration in terms of reduced induced drag due to inhibition of wingtip vortices to lead to the lowest fuel burn. Conventional aircraft on the other hand generally have aspect ratio values of around 9-10. Most of the configurations for three of the missions analysed found a minimum aspect ratio at the lower side of the range investigated but not at the absolute minima as the aerodynamic efficiency of the aircraft did have some influence on the configuration with the lowest fuel burn.

6.4. Combining Vertical Wing Separation and Aspect Ratio

In the previous chapter, the influence and interaction of the vertical wing separation and aspect ratio was explored together to find the optimal design point for each of the missions concepts. With the horizontal wing separation between the wings being optimal the lowest value for all the missions, this allowed for the fuel burned by the box-wing for each mission to be compared to the fuel burned by the conventional. For example, for Mission 1, the following carpet plot was created.

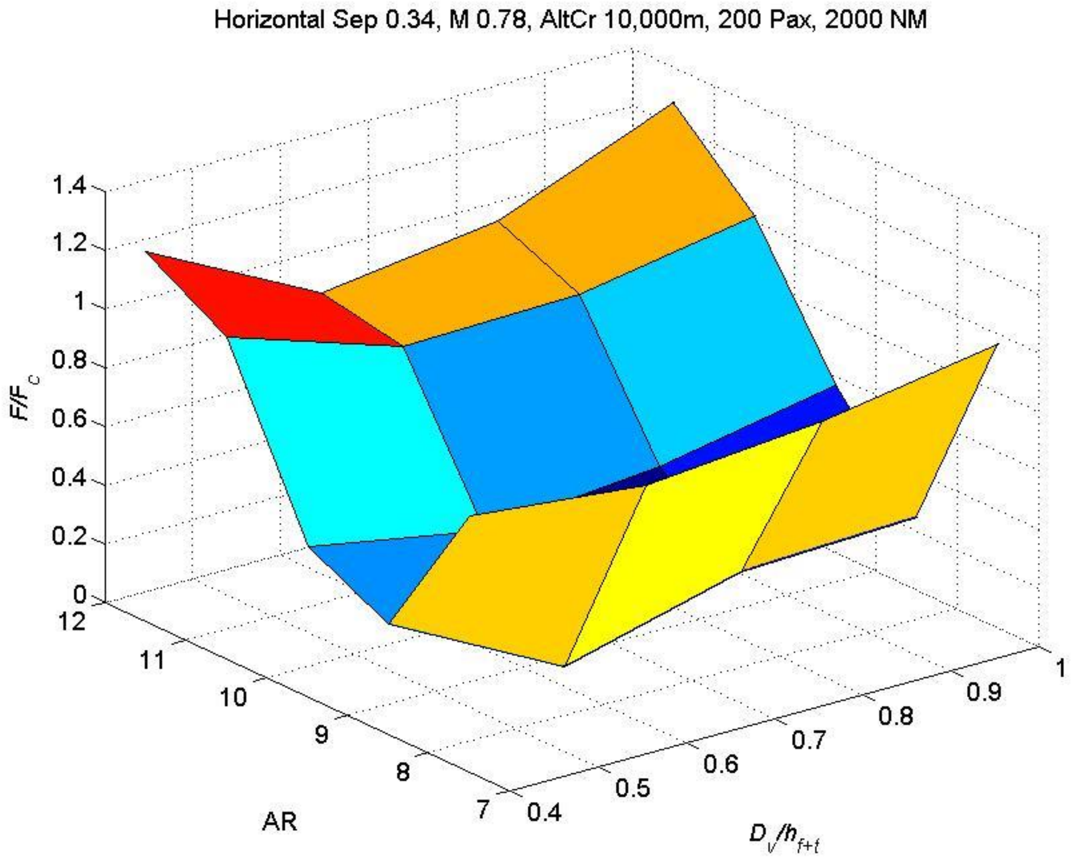


Figure 6-9 Optimisation using vertical wing separation and aspect ratio for Mission 1

The combined analysis shows that such a minimum value does exist for this particular mission scenario, where the right choice of aspect ratio and vertical wing separation together do lead to an optimum result. The general relationships between the two parameters are also established, so that if other considerations do dictate a design point in terms of geometry that is not ideal that lies elsewhere on this surface, the design team can quickly identify how much more or less efficient that set of parameters would be if a box-wing was considered over the conventional planform, and whether to proceed with the box-wing over the conventional design.

The comparison is a little clearer using a more straightforward set of curves, shown in Fig 6-10 (same as Figure 5-4 in Chapter 5). Here it can be seen for Mission 1, for every aspect ratio the most optimum vertical wing separation value is 6 metres.

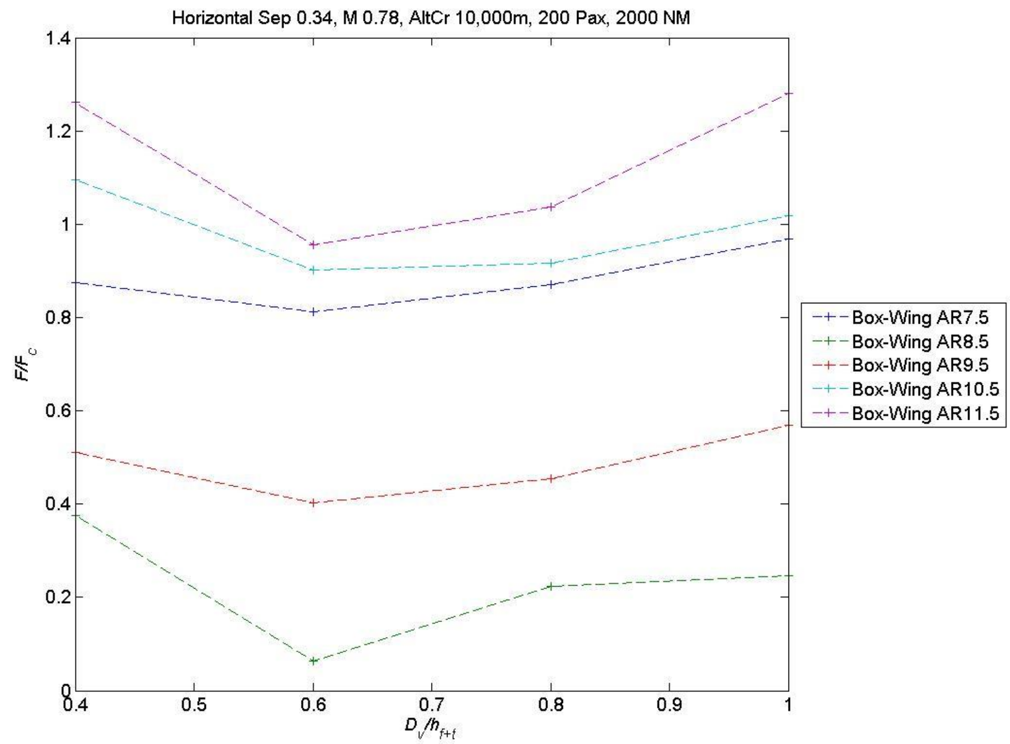


Figure 6-10 Fuel burn versus aspect ratio and vertical wing separation for Mission 1

From this, it becomes apparent that for every aspect ratio, the non-dimensional vertical wing separation being at 0.6 (6 metres, relative to the overall height of the aircraft) offers the most efficiency in terms of fuel burn when compared to the conventional design. The lesson offered by the aspect ratio analysis, that lower aspect ratio wings that offer greater structural benefits are actually overall more likely to increase the effiency of the configuration, as opposed to higher aspect ratio wings that offer more aerodynamic advantages, are also further borne out by this extended investigation as the aspection ratio of 8.5 offers a decrease in fuel burn compared to the others.

The best combination of geometric parameters for this particular mission for a box-wing configuration is then found to be a D_v of 0.6, a D_h of 0.34 and an aspect ratio of 8.5. A wing planform with those dimensions is shown in Figure 6-11.

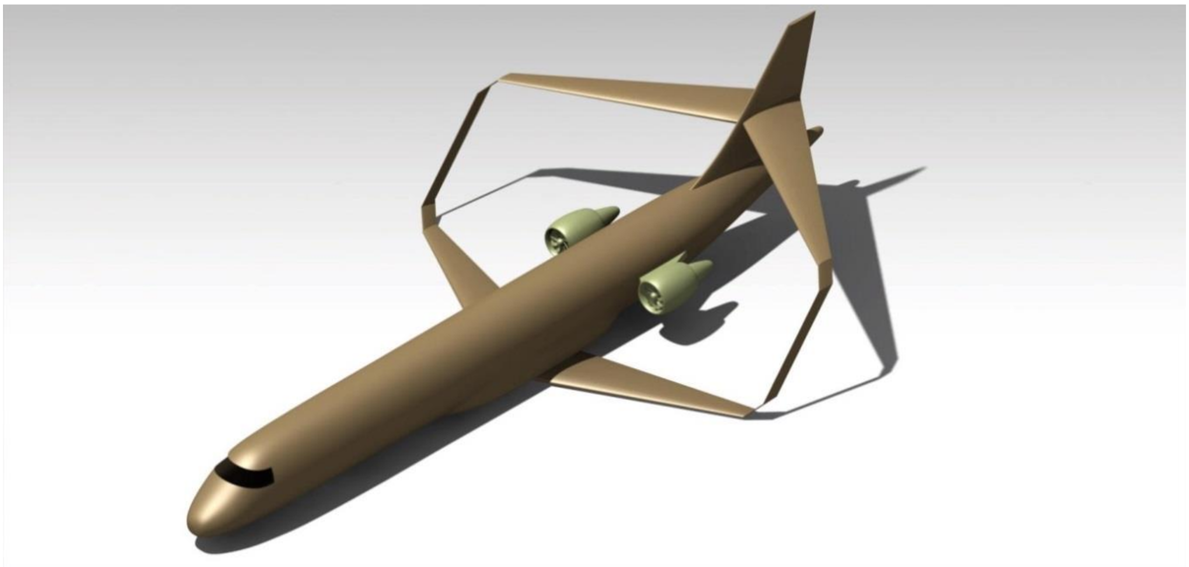


Figure 6-11 Optimal box-wing geometry for Mission 1

The other missions have very similar ideal configurations that lead to minimum fuel burn, showing that the trends and design drivers identified from the parameter sweeps behave in a similar fashion across all missions. The carpet plots in Figures 6-12 through to 6-14 show the behaviour of the variables while Table 6-1 outlines the optimal combination of geometric parameter for each mission.

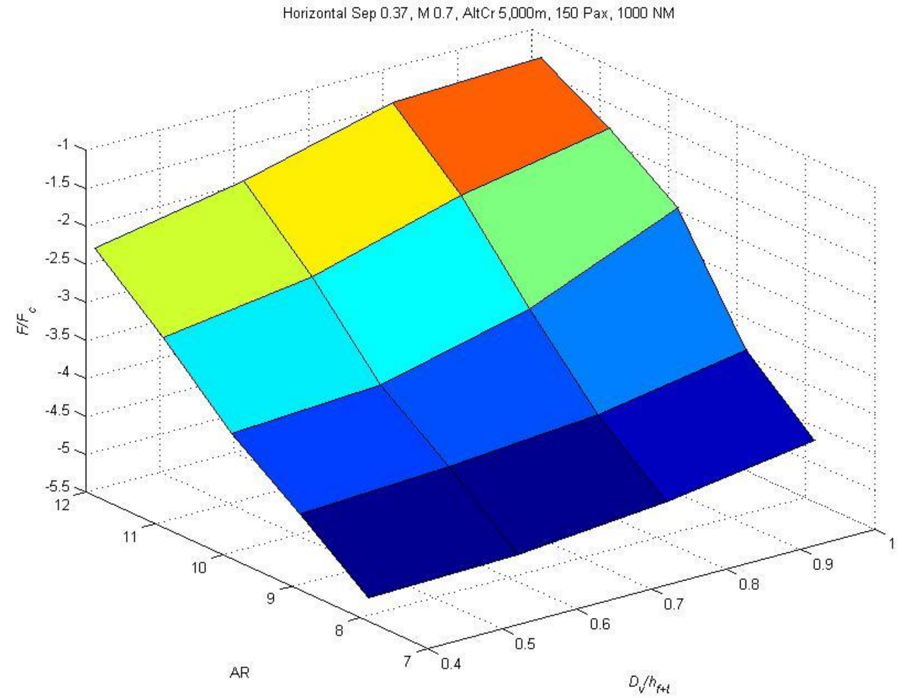


Figure 6-12 Optimisation using vertical wing separation and aspect ratio for Mission 2

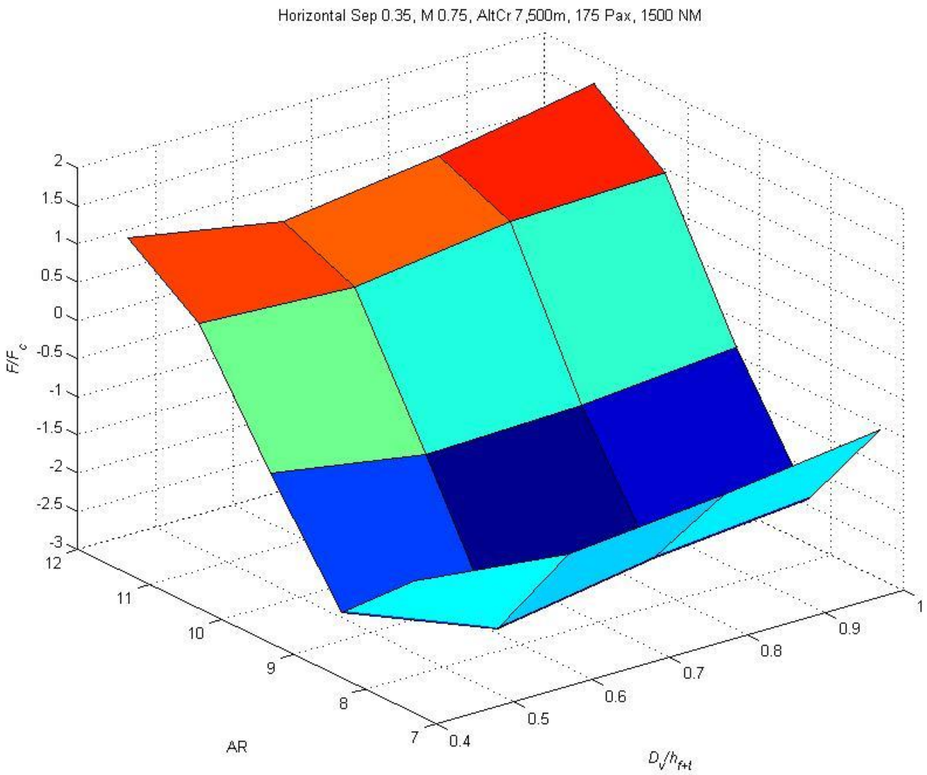


Figure 6-13 Optimisation using vertical wing separation and aspect ratio for Mission 3

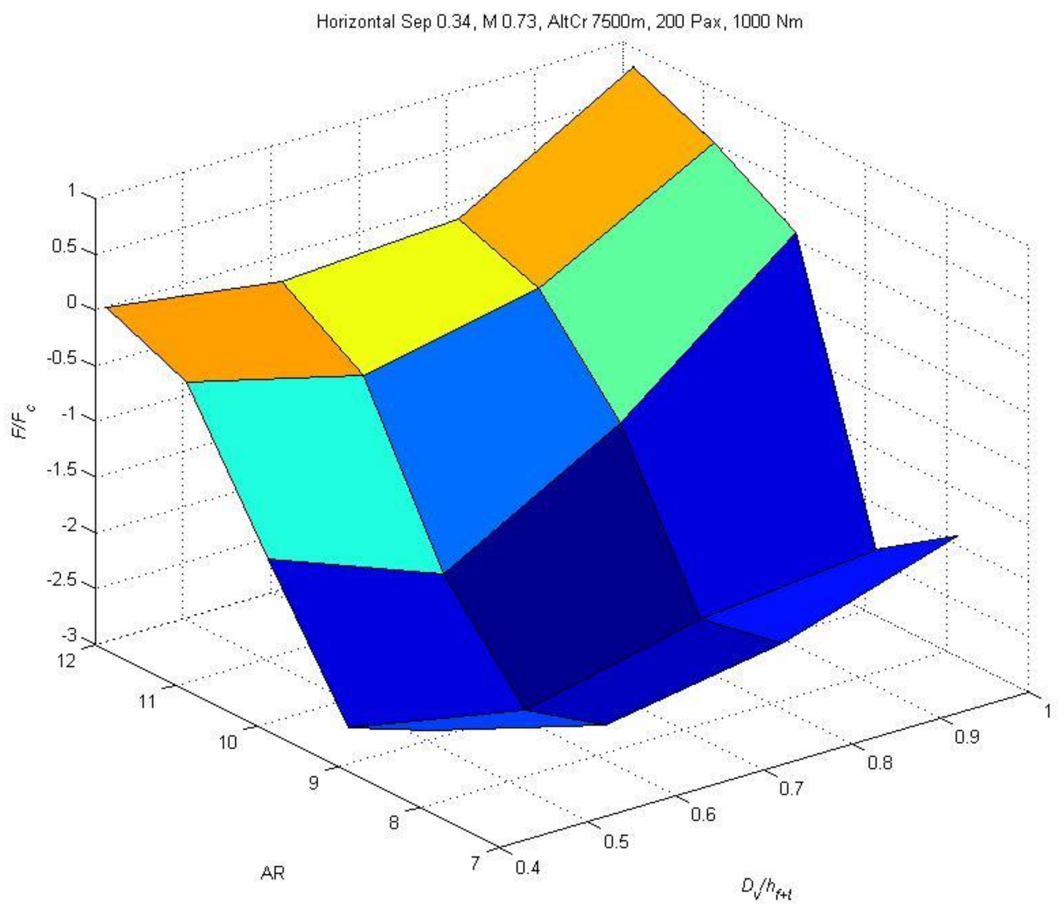


Figure 6-14 Optimisation using vertical wing separation and aspect ratio for Mission 4

Table 6-1 Optimal geometry values for different missions

Mission	**Horizontal Wing Separation (D_h/l_f)**	**Vertical Wing Separation (D_v/h_{f+t})**	**Aspect Ratio**
1	0.34	0.6	8.5
2	0.37	0.4	7.9
3	0.35	0.6	8.3
4	0.34	0.6	8.9

As can be seen, the horizontal wing separation was at the minimum value for each of the missions (the change is due to the slight variation in fuselage length required due to different passenger capacity requirements from the payload), and the geometric values for aspect ratio and vertical wing separation largely trended similarly. The variation in between missions will be discussed in the next chapter.

The effect of the horizontal wing separation is relatively clear, but it is more important to parse out the effects of the aspect ratio variation and the vertical wing separation on the box-wing's aerostructural qualities and hence performance. From the relative improvement in fuel burn offered by the two parameters, it is clear that the vertical wing separation effect is dominated by the aspect ratio effect. From the importance of aspect ratio to conventional wing design, this is not an unexpected outcome, with the improvement in structural efficiency significantly more dependent on allowing the wings to be shorter and more efficient in carrying the requisite loads. Conversely, the improvement in aerodynamic efficiency from increasing the vertical wing separation between the two horizontal wings is relatively small. Most of the aerodynamic improvement comes from switching to the box-wing configuration and taking advantage of its inherent reduction in induced drag rather than increasing the vertical wing separation once the configuration is in use.

The geometric characteristics of the configuration also have impacts on the design beyond the performance outcomes discussed so far, which are also worthy of consideration even at the conceptual design stage. Wings with lower aspect ratios, as per the optimal designs found from the geometric parameter sweeps, will have significantly lower wingspans than conventional configurations. For example, for Mission 1, the conventional configuration has a wingspan of 36.5 metres, while the ideal box-wing configuration has a wingspan of 17.3 metres. The significant difference arises from the combination of the lower aspect ratio per wing, and the division of the total reference area over two wings for the box-wing, of course. This means that airports will be able to fit more box-wing aircraft into the same space as they will not need to be spaced out as much as current conventional designs.

Another benefit to the lower vertical wing separation between the two horizontal wings is that the rear wing does not necessarily need to be supported by the vertical tailplane. When the D_h is 0.4, that is actually the top of the fuselage and the structural loads can be run through the fuselage itself. Even at a D_v of 0.6, the structural loads are much closer to the bottom of the vertical tailplane and only a smaller segment of it needs to be strengthened in order to effectively support the rear wing and the aerodynamic loads it is carrying. In contrast, when the D_v is 1.0 the entire vertical tailplane structure will need to be much stronger and heavier to support the rear wing and the loads that will placed upon it, increasing the overall weight of the aircraft and leading to additional fuel burn.

Maintenance and manufacturing of the aircraft will also be easier when the vertical wing separation between the wings is lower, with access to the rear wing much less problematic if it is at the fuselage or lower tailplane height than at the top of the vertical fin. Aircraft wings require significant inspection and maintenance and being able to conduct that without needing to scale the height of the aircraft will save both time and money. While this benefit cannot be easily quantified, its existence is necessary and important to note, even at the conceptual design stage of the process.

Hence the geometric parameter sweep and optimisation conducted at this stage of the process is an incredibly important part of the conceptual design stage for the box-wing aircraft, and one that is absolutely necessary if designers are to find the ideal configuration that will suit their mission and bring the greatest reduction in fuel burn possible.

7. Mission Analysis

7.1. Impact of Mission Requirements

The mission concepts that were used to design the conventional and box-wing configurations for this analysis are summarised, as they will be critical for this chapter's discussion. The optimised configurations are presented in Figs 7-1 through to 7-4.

Table 7-1 Parameters for missions investigated (presented previously as Table 4-1)

Mission	Number of passengers	Range	Cruise Mach Number	Cruise Altitude
1	200	3704 km (2000 NM)	0.78	10000 m
2	150	1852 km (1000 NM)	0.7	5000 m
3	175	2778 km (1500 NM)	0.75	7500 m
4	200	1852 km (1000 NM)	0.73	7500 m

Table 7-2 Optimal geometric parameter values for each mission (presented previously as Table 6-1)

Mission	Horizontal Wing Separation	Vertical Wing Separation	Aspect Ratio
1	0.34	0.6	8.5
2	0.37	0.4	7.87
3	0.35	0.6	8.32
4	0.34	0.6	8.87

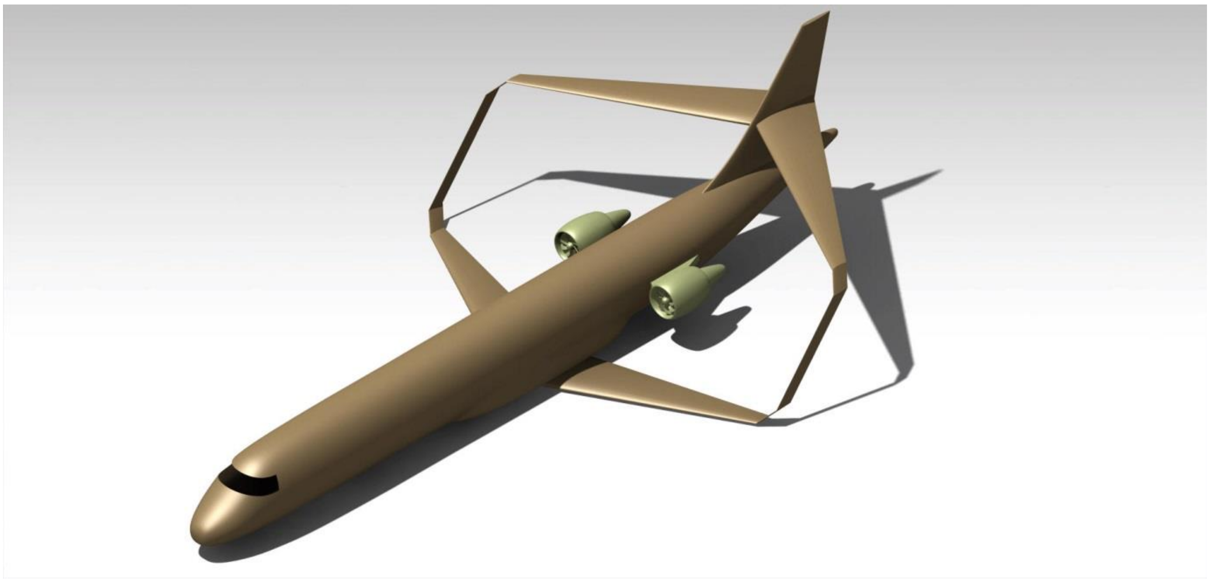


Figure 7-1 Optimal box-wing geometry for Mission 1

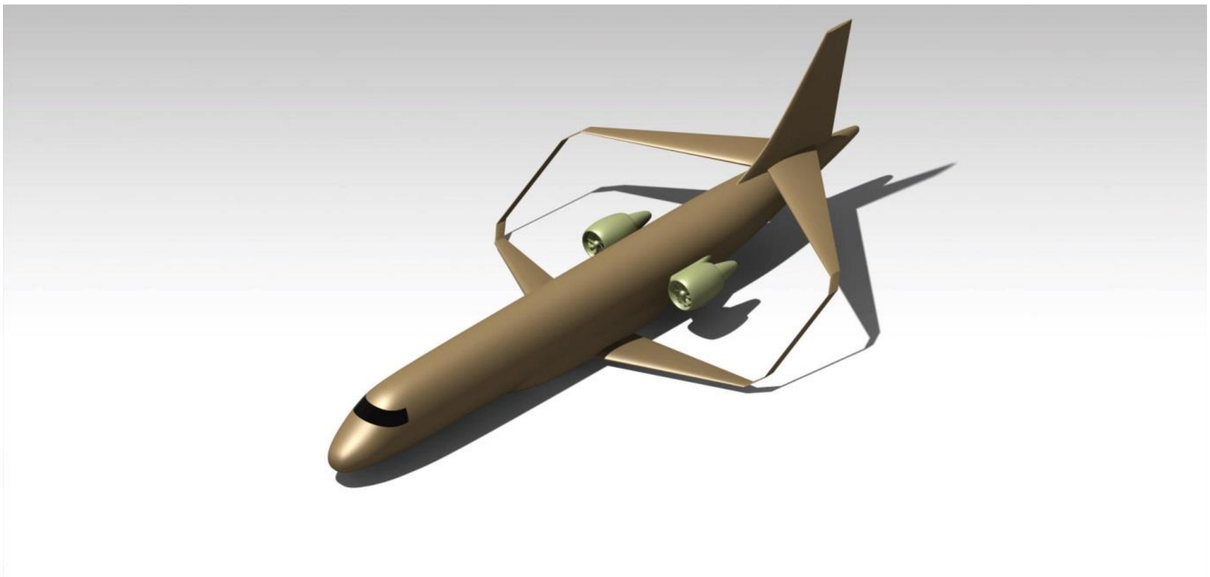


Figure 7-2 Optimal box-wing geometry for Mission 2

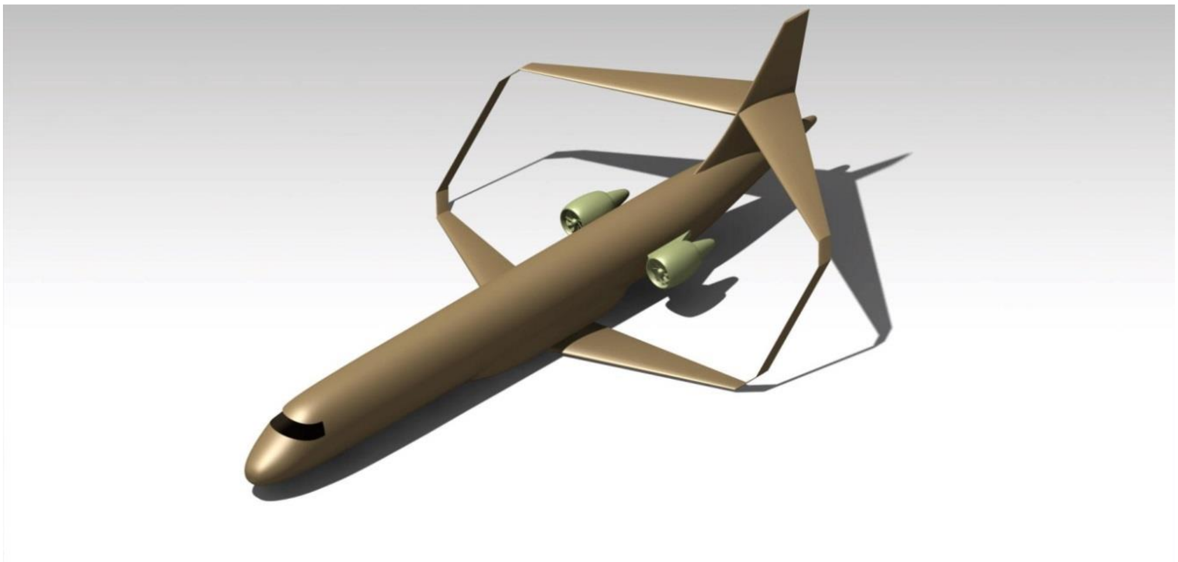


Figure 7-3 Optimal box-wing geometry for Mission 3

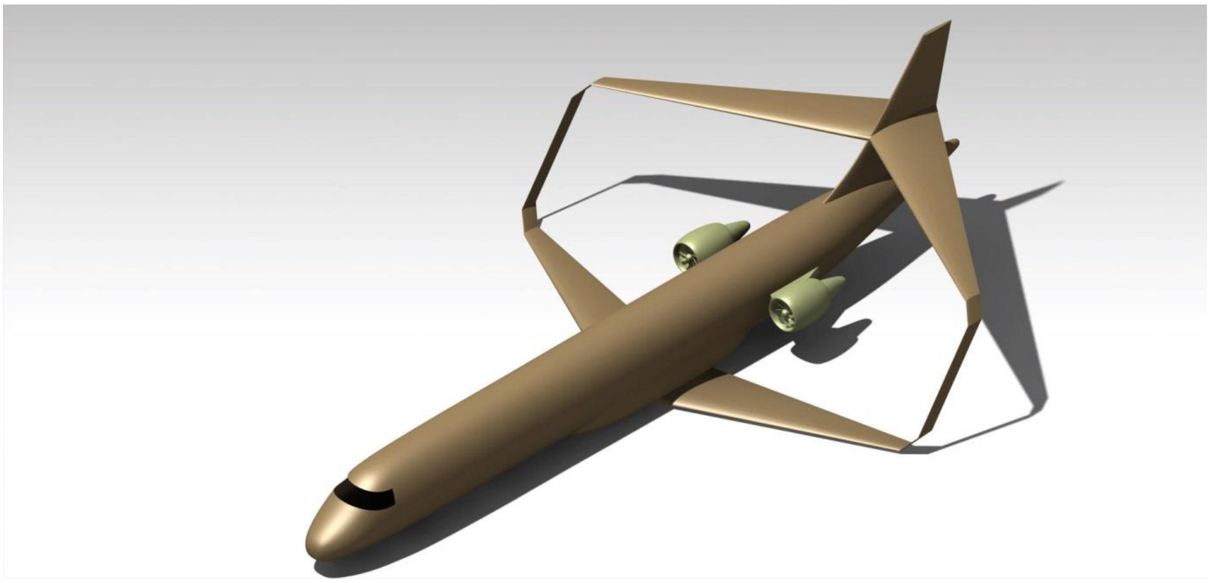


Figure 7-4 Optimal box-wing geometry for Mission 4

The outlier amongst the geometric configurations for the four missions is Mission 2, with the lowest required vertical wing separation and also the lowest aspect ratio, while the others are more in the middle of their respective ranges of values. This is due to the mission for this aircraft being the least aerodynamically demanding, and hence requiring the lowest lift-to-drag ratio in order to fulfil the requirements. The box-wing configuration is able to significantly increase the structurally efficiency with the lowest vertical wing separation and the aspect ratio while at the same time for this particular mission the aerodynamic losses are not significant enough at those values to drive the design away from maximum structural efficiency. The other concepts, with higher payloads, speeds or altitudes require at least somewhat of a trade-off between the maximum structural efficiency and the aerodynamic demands from the mission requirements.

Once the four missions are considered side by side, a picture emerges of the relative weights and trends with regards to the ideal box-wing configurations and fuel burn reductions they offer. Most importantly, the greatest reduction is from Mission 2, which was the aircraft with the lowest and slowest missions, with the smallest payload. Mission 1, with the longest mission and the largest payload, achieved no improvement in fuel burn with the box-wing configuration while the optimal configurations for Missions 3 and 4 were able to achieve relatively small reductions in fuel burn.

Table 7-3 Comparison of fuel burn, weight and aerodynamic performance of missions

Mission	**Fuel Burn (Box-Wing relative to conventional)**	**MTOW (Box-Wing relative to conventional)**	**L/D (Box-Wing relative to conventional)**
1	+0.06%	0.93	0.93
2	-5.19%	0.89	0.94
3	-2.94%	0.89	0.92
4	-2.91%	0.93	0.96

There are several reasons as to why the improvement in fuel burn behaves in this manner for the different missions analysed. As is clear from the improvement in MTOW, the larger the aircraft and payloads, the lower the improvement possible from switching to a structurally-efficient box-wing configuration. This is due to the fact that the wing mass, and the improvement possible via structural optimisation, forms a smaller part of the overall mass of the aircraft. Hence even after optimisation, the improvement offered by the ideal box-wing configuration is not as large as for the smaller aircraft concepts. This is clear from the comparison of Missions 1 and 4, the two aircraft with the largest payloads and hence overall larger MTOWs, with Missions 2 and 3 which have smaller payloads and smaller MTOWs.

While Mission 1 and Mission 4 have similar differences in MTOW and lift-to-drag when considering the ideal box-wing and conventional, the relative improvement in fuel burn for Mission 4 shows the influence of the other mission parameters. Mission 4 flies for half the range, at a much lower cruise Mach number and cruise altitude. Flying for shorter distances at lower and slower cruise conditions then bring an improvement in the fuel burn when considering the relative performance of the box-wing to the conventional. This is expected, as these requirements mean less influence of the lift-to-drag ratio and a greater impact from the structural improvements offered by the box-wing. The penalty of lower aerodynamic performance for the box-wing is less meaningful when the mission requirements are relaxed, and this is played out with Mission 2 having the greatest reduction in fuel burn for the lowest and slowest mission.

The mission parameters then are very important when considering whether a box-wing configuration is suitable and will offer an improvement in fuel burn over the conventional cantilever configuration, and should definitely act as a design driver. In this case, it is clear that the right combination of range, cruise Mach number, cruise altitude and payload will determine whether an optimised box-wing configuration is able to deliver a reduction in fuel burn or not. When the mission requirements tend towards slower and lower flights, even amongst short-range cityhopper scenarios that is when the box-wing is able to offer an advantage in efficiency.

The other point to note is what kind of missions do not lead to a fuel saving when considering the box-wing configuration, which is when the mission payload is larger and the mission itself is at higher speed and altitude over longer distances. In these cases the natural advantages of the box-wing are minimised, as the conventional configuration achieves a better balance of lift-to-drag ratio (with zero-lift drag's effect dominating over longer ranges) and the improvement in overall weight from the structurally-optimised wing becoming less important as the overall MTOW of the aircraft increases. This has been borne out by other design investigations which focus on the box-wing configuration being used for longer-range missions with larger payloads, but the lack of improvement for those missions should mean that designers should not consider the box-wing when the mission requirements do not suit its strengths. From the missions analysed here, it is clear that when the payload is greater than 200 passengers, and the cruise range of 2000 nautical miles being flown at a cruise Mach number of 0.78 and at 10000 metres altitude, the box-wing will not offer an improvement over the conventional configuration. If the requirements exceed those, then the box-wing does not serve as a suitable alternative concept to the conventional for a goal of reducing fuel burn. For missions under those requirements, the box-wing should be considered at the conceptual design stage as it does offer a potential improvement in fuel burn and design teams need to utilise that improvement.

The take-off and landing phases of flight, while not considered for the optimisation and analysis in this study, will also further contribute to the improvement in fuel burn offered by the box-wing. These phases of the flight, especially the take-off phase, are where the most lift is generated by the aircraft, meaning that is also where the most lift-induced drag is generated by the aircraft. The natural advantage of the box-wing in terms of reducing induced drag will be especially apparent during this phase of flight, as the less energy loss will need to be overcome and hence less fuel will be burnt by the box-wing as opposed to the conventional configuration. The box-wing will hence become even more attractive once the detailed design phase begins to take those effects into account.

These cityhopper aircraft concepts will likely become an attractive mission niche in the civil market, as the growth of air traffic in continents such as Asia, South America and Africa becomes paramount and city pairs that are relatively close together, in the vicinity of 1500 nautical miles, continue to dominate the actual missions flown by the majority of single-aisle twin-engine aircraft. Manufacturers and airlines need to come together and consider the box-wing concept as a viable configuration for those mission niches, as significant fuel savings are possible.

7.2. Effect of More Triangular Lift Distribution

The effect of the lift distribution on the aerostructural analysis of a wing planform can be significant, as noted in Chapter 2, Section 2.3, and the assumption here that the elliptical load distribution chosen at the start as per Prandtl-Munk Theorem for most efficient results should also be considered carefully. While the classical elliptical lift distribution is more efficient when considering just aerodynamics, there have been investigations that have found that a more triangular lift distribution that is more highly loaded at the root of the wing and carries less loads at the tips was more efficient when considering both structures and aerodynamics (Jansen & Perez, 2010), though subsequent studies have also disputed this finding (Takahashi, 2012).

Therefore, for this analysis, one of the configurations was re-analysed using the same toolchain but with the condition of the elliptical lift loading removed for the aerodynamic and structural optimisation. Instead, as per the previous literature studies, a more triangular loading with 10% greater lift at the root was imposed on the two horizontal wings of the box-wing as well as the conventional configuration that was the baseline aircraft. In this case the Mission 2 concept was chosen for comparison and only two vertical separations were considered- the minimum and that maximum of 0.4 and 1.0, and three aspect ratios of 7.87, 9.87 and 11.87.

The results can be seen in Fig 7-5, and the comparison with the same configurations with the elliptical lift distribution can be seen in Table 7-4. In this case, the more triangular lift distribution does lead to an improvement in the efficiency for the baseline conventional configuration but there is little to no improvement in efficiency for the box-wing, which means that the box-wing configurations are not as fuel efficient compared to the conventional when the elliptical lift distribution is chosen as the basis of the analysis. The reason for this result is that the primary benefit of the more triangular lift distribution is a reduction in the weight at the tips of the wing for an overall small increase in induced drag. However, the box-wing configuration does not gain that weight reduction due to the fact that the tips must support the loads flowing through the vertical wing, and the movement of the other horizontal wing. The ribs and spars at the tips of the box-wing are significantly heavier than those of the conventional configuration. The box-wing configurations that see the most benefit out of the more triangular lift distribution are the high aspect ratio configurations, in terms of weight, as there is a small reduction in weight at those high aspect ratios as the slim tips of those wings do not have to support as high a load when the more triangular lift distribution is used. However, the increase in the efficiency gained by the conventional configuration overtakes this increase in efficiency, leading to an overall increase in the fuel burn by the box-wing configuration compared the conventional with the more triangular lift distribution for the highest aspect ratio configuration.

It must be noted that this analysis only takes into account the failure modes of bending and buckling, and does not include other failure modes such as fatigue or flutter, as well as loads from other phases of flight such as take-off and landing. If those are also incorporated into the analysis, it is possible that the conventional wing planform would also perform worse under the more triangular lift distribution.

Figures 7-6 and 7-7 show the difference in the Von Mises stresses when the more triangular load is compared to the elliptical load for the conventional and the box-wing configurations. For the conventional configuration, it becomes clear that the more triangular loading distribution leads to higher stresses inboard of the wing, towards the root, which is clear with the higher maximum stress concentration as per the legend. Hence the structural material can be concentrated in those areas, leading to an overall weight saving. In contrast, with the elliptical load distribution the stress manifests more evenly through the span of the wing. With the box-wing, the stresses at the tips, where the horizontal wings are joined to the vertical wing, are present no matter which loading distribution is used and hence the weight savings do not manifest when the box-wing is under the more triangular wing loading and the maximum stresses and the distribution of the stress is remarkably similar under both loading conditions.

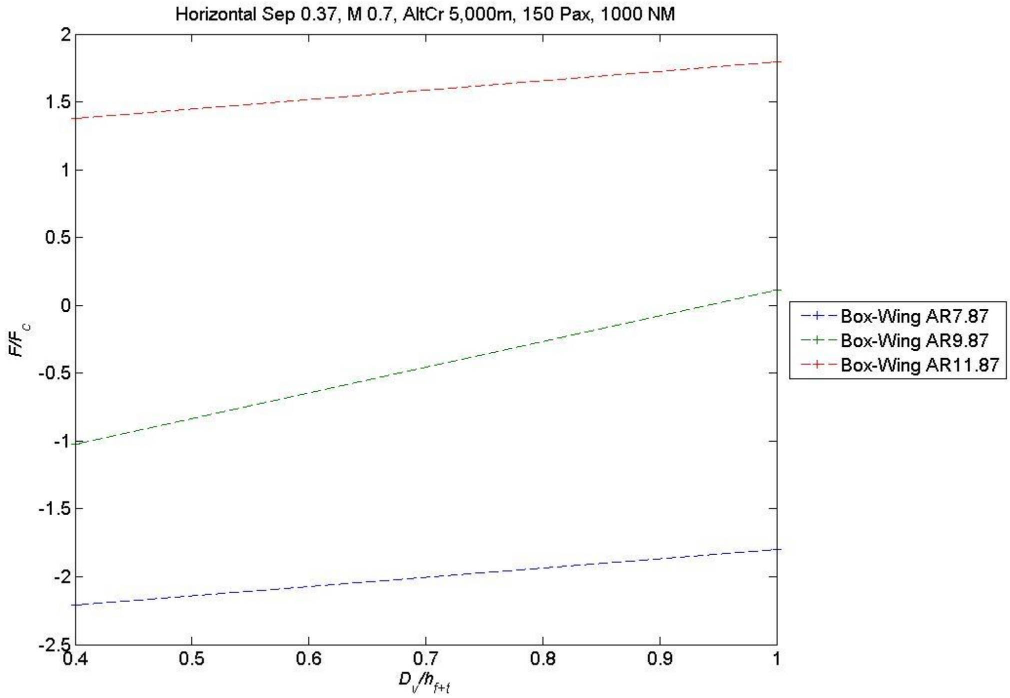


Figure 7-5 Mission 2 Fuel burn versus vertical separation and aspect ratio comparison with more triangular lift distribution used as basis for analysis

Table 7-4 Comparison of fuel burn, weight and aerodynamic performance of missions

Aspect Ratio and Vertical Separation	Fuel Burn Comparison (Elliptical Lift Distribution)	Fuel Burn Comparison (More Triangular Lift Distribution)
7.87, 0.4	-5.19%	-2.2%
7.87, 1.0	-4.7%	-1.8%
9.87, 0.4	-3.85%	-1.0%
9.87, 1.0	-2.45%	0.11%
11.87, 0.4	-2.23%	1.38%
11.87, 1.0	-1.3%	1.8%

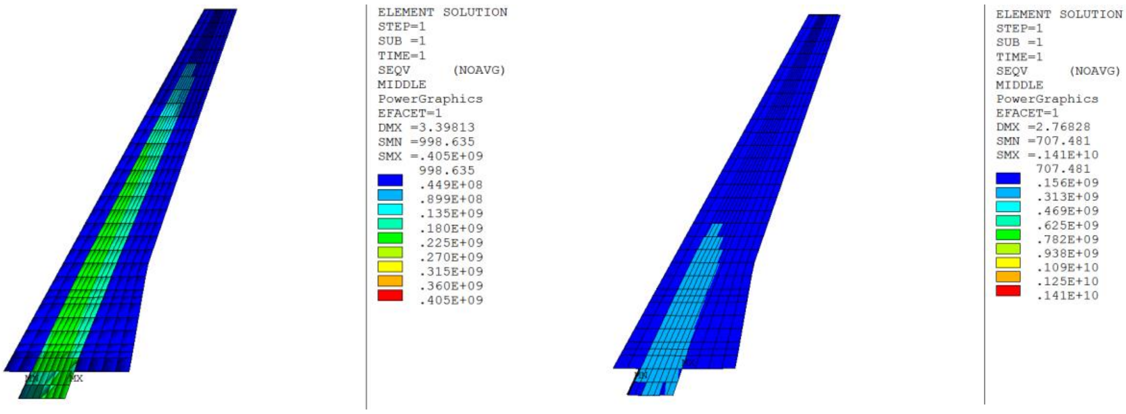


Figure 7-6 Mission 2 Conventional configuration Von Mises stresses with elliptical (left) versus more triangular (right) wing load distribution

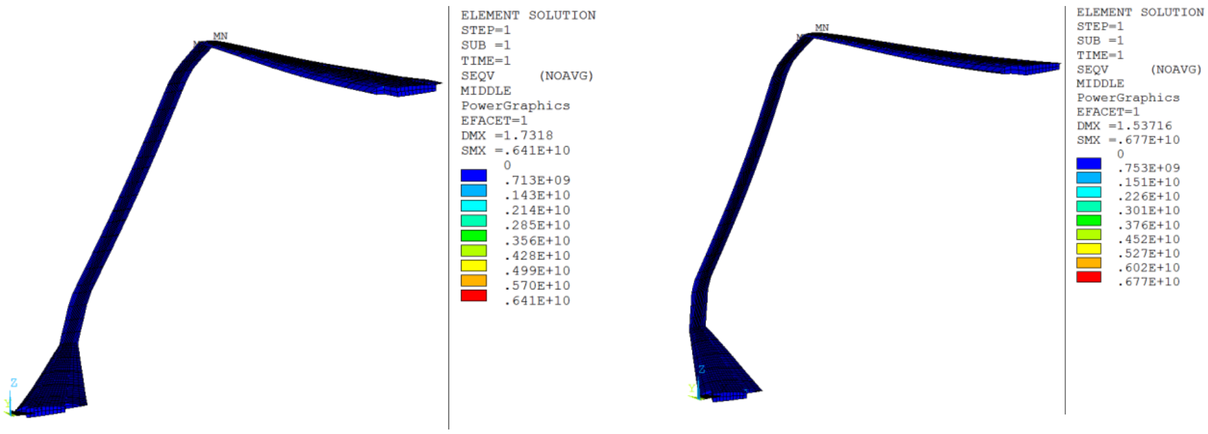


Figure 7-7 Mission 2 Conventional configuration Von Mises stresses with elliptical (left) versus more triangular (right) wing load distribution

Hence it can be seen that in the case of the more triangular lift distribution, the box-wing configuration actually suffers in comparison to the conventional configuration when this condition is imposed. The necessary structural weight is already at the tips of the horizontal wings for the box-wing and must stay there to support the vertical wing and loads it is under, and the weight reduction promised by the more triangular lift distribution hence cannot be achieved for the box-wing. The change in the induced drag is not enough to offset this disadvantage, especially as can be seen from Chapter 6 that the effect of the change in structural weight often dominates the effect of the change in induced drag for the box-wing for this mission scenario. In this case, the classical elliptical lift distribution is the more suited lift distribution for the box-wing though the conventional configuration could possibly be improved if the more triangular lift distribution was used in terms of the analysis as per previous studies (Jansen, et al., 2010).

7.3.Weight and Balance Considerations

This optimisation from the aerostructural analysis presents aircraft configurations that will need to be modified for weight and balance issues. In particular Figs 7-1 to 7-4 show the front wing is too close to the engines and the rear of the aircraft, and will need to be moved further forward so the lift from that wing has a larger moment arm considering the centre of gravity of the aircraft. The horizontal wing separation between the wings can be modified to increase this distance, though there is a small penalty to be paid in terms of the efficiency gained from the box-wing configuration which is maximised when the horizontal wing separation is at its minimal value.

If Mission 2 is used as an example, the horizontal wing separation can be increased from 0.37 to 0.48 of the length of the fuselage to an estimated value which will lead to a reasonable improvement in the weight and balance and hence the centre of gravity of the aircraft, while the aspect ratio and vertical wing separation are kept at the optimal values. This changes the improvement in fuel burn from -5.19% to -3.96%, still showing a significant improvement in the fuel burn overall compared to the conventional. The configuration with this horizontal wing separation is shown in Fig. 7-6, and the concerns regarding the weight and balance of the configuration are alleviated. In this manner, the horizontal wing separation can also be changed for improved performance in other disciplines such as stability and control.

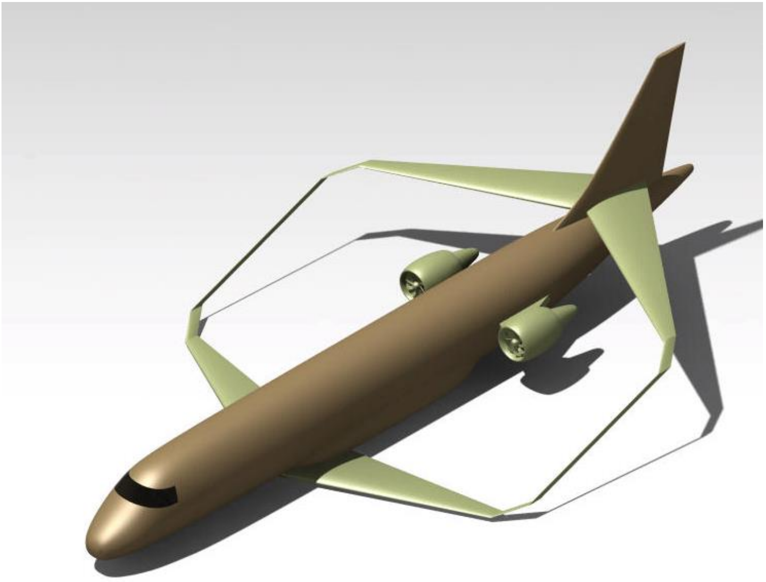


Figure 7-8 Mission 2 box-wing configuration with horizontal wing separation of 0.48, vertical wing separation of 0.4 and aspect ratio of 7.5

When considering all the missions, and the impact of changing the horizontal wing separation to a value that improves the weight and balance aspect of the aircraft, the following changes in the performances are noted. This shows that the horizontal wing separation offers a flexible variable to the designer that can be utilised to address concerns arising from other design disciplines while maintaining as much of the aerostructural optimisation as possible for a box-wing configuration.

Table 7-5 Fuel burn improvement after taking weight and balance into consideration

Mission	Optimised Fuel Burn Reduction	Fuel Burn Reduction After Weight and Balance
1	+0.06%	+1.12%
2	-5.19%	-3.96%
3	-2.94%	-1.43%
4	-2.91%	-2.11%

7.4.Accuracy and uncertainties

Comparing these fuel burn results is somewhat difficult due to some of the assumptions and errors that creep into the analysis. The specific fuel consumption for the chosen engine, for example, is for the cruise altitude and mission it is designed for, yet here it is being used for off-mission analysis, especially for the concept aircraft designed for lower cruise altitudes and Mach numbers. While the relative nature of the results (comparing the box-wing against the conventional) eliminate some of the uncertainty, comparing the results to each other should be done after taking into account the existence of these kinds of assumptions.

One particular assumption that analysis is sensitive to is with respect to the Q factors for the interference drag of the box-wing, which have to be assumed as no hard data exists with respect to this configuration and those factors are very difficult to calculate numerically without multiple high-level CFD analyses. In this case, assuming a higher Q factor would leave to a reduction in the performance of the configuration across the board with respect to each mission, meaning that the fuel burn of the box-wing would be higher relative to the conventional. For the optimal designs this could lead to a reduction in the efficiency gain by several percent, depending on how much the Q factor was increased. Hence it is absolutely critical that when further, detailed analysis of the box-wing configuration is conducted, based on the optimal designs recommended in this study, that a far more in-depth, high-fidelity analysis of the interference drag is part of that so the behaviour of the parasitic drag with regards to the box-wing is better understood and can be better modelled.

The other uncertainty that has a large impact on this comparison in particular is the prediction of the zero-lift drag, which definitely needs to be refined further with more advanced methods. This value plays an extremely large part in the evaluating the aircraft’s fuel burn for any given mission, and even a small change in the figure can have a large impact on the fuel burn value for that mission, especially for longer flights.

8. Conclusions

8.1 Principal Findings and Research Objectives

A multidisciplinary conceptual design analysis was developed for comparing the box-wing with conventional cantilever aircraft configurations, for reduced fuel burn as per the aim of the research. Structural and aerodynamic disciplines were analysed, optimised and integrated so the ideal design points in the design space for the box-wing in terms of geometric parameters could be found for a given short-range mission scenario. The key findings are presented below in response to the objectives set by the research questions in Chapter 2.

8.1.1 What is the best framework and associated processes for conducting a multidisciplinary design analysis of a box-wing aircraft configuration for a given mission scenario?

The critical aerodynamic and structural components of the toolchain were linked and integrated into a methodology and toolchain that allows designers to evaluate the box-wing fairly against conventional aircraft for any given mission. The relatively fast exploration of a design space means that box-wing configurations and design points that would not have been previously investigated and explored were able to be analysed and found to be important when considering the most fuel efficient aircraft. The use of a common language (CPACS) and integration of tools via that language and database provide a valuable resource for future designs as an important stepping stone to further high-fidelity research into the configuration, while the results being relative to conventional configurations designed for those mission parameters mean that comparison between the results is more trustworthy than comparing to existing aircraft optimised for other mission scenarios and can be relied upon for greater fidelity.

8.1.2 What are the effects of geometric parameters of the box-wing configuration and the interaction of aerodynamic and structural characteristics, on overall fuel burn?

The key findings with regards to the geometric parameters were that the optimal aspect ratio and vertical wing separation occurred at lower values, and hence the entire design space should be explored when considering box-wing aircraft so the correct design point can be found. The influence of the horizontal wing separation was low due to the small impact on the aerodynamic and structural characteristics of the aircraft from increasing the horizontal wing separation of the wing, and that parameter can be designed for reasons other than aero-structural optimisation such as stability and control. For the aero-structural optimisation, the lowest wing horizontal separation was found to be ideal for all configurations and mission scenarios.

The aspect ratio and vertical wing separation values that led to the lowest fuel burn actually occurred at relatively low values. This was due to the fact that the box-wing configuration actually offered significant structural benefits at those lower values and the aerodynamic penalties that would generally be associated with those designs were offset by the inherent advantages of the box-wing. Conventional wings would suffer from very large increases in induced drag when considering aspect ratios and wing spans of such a nature, but the box-wing configuration ensures the flow stays more attached around the whole wing system and hence allows the structural efficacies to be gained with minimal aerodynamic disadvantages. Overall this leads to an improvement in fuel burn over the course of the cruise phase of the mission for the aircraft investigated in this analysis.

8.1.3 How do mission requirements influence a box-wing configuration design of a short-range aircraft?

The box-wing is best suited for short-range missions at lower altitudes and lower cruise Mach numbers because those requirements maximise its advantages and minimise its advantages in terms of the aero-structural efficiency it offers over the conventional. The maximum reduction in fuel burn offered by a box-wing configuration in comparison to a conventional configuration was about 5% for Mission 2. Conversely for long-range, high altitude and high cruise Mach numbers, the box-wing was not able to offer a reduction in fuel burn over the conventional configuration with even the optimum configuration leading to a 0.1% increase in fuel burn. Large aircraft for a short range mission scenario is another option where the box-wing could present a viable improved alternative to the conventional, for high frequency city pairs that are not very far apart and serviced by aircraft not currently designed and optimised for those missions. Mission 4 presents a case for this scenario, where the box-wing configuration offers almost a 3% saving in fuel burn compared to the conventional configuration.

Thus when the appropriate mission requirements are present i.e. small payloads to be flown short distances at low cruise altitudes and Mach numbers, the box-wing configuration should be considered as an option next to the conventional. The city-hopper, short range mission niche is where its advantages can be maximised and disadvantages minimised and hence it offers the improvement in terms of fuel burn and environmental impact.

8.1.4 What improvement in fuel burn can be achieved with the box-wing configuration over a conventional aircraft for a given mission?

The maximum fuel burn reduction offered by the box-wing was 5.2% compared to the conventional configuration for the mission with the lowest cruise Mach number, altitude, range and payload (Mission 2). Missions 3 and 4 offered reductions of 2.9% each. Mission 3's parameters fell in the median between the extremes investigated, while Mission 4 considered a large aircraft with the maximum payload flying a short-range mission as per that scenario for busy city pairs located relatively close together. These reductions are still significant, especially when considered over the life of a fleet of such aircraft and the missions they might fly. The only mission not to show reduction in fuel burn was Mission 1, which considered an aircraft flying the longest range with the heaviest payload at the maximum cruise altitude and Mach number in the range investigated, where the advantages of the conventional configuration outweighed the box-wing.

8.2 Contribution to Body of Knowledge

The following key contributions to knowledge were made from this research.

- Aero-structural methodology and toolchain for design space exploration and optimisation was developed and applied to the box-wing. Various analytical tools were connected via a common XML database (CPACS).
- The key geometric parameters for optimising box-wing configurations the aspect ratio and vertical wing separation.
- The horizontal wing separation was found to have minimal influence because of the relatively small changes it has on the weight and aerodynamic performance, and can be used for other design concerns, not aero-structural optimisation.
- Aero-structural efficiency was gained via reduction in fuel burn when the aspect ratio and vertical wing separation were either minimised or on the lower end of the spectrum of values, not maximised.
- Importance of aero-structural methodology and toolchain was shown as the interplay between the aerodynamic and structural aspects of the design led to the optimum design points.
- It was found that lower and slower missions offer the best reduction in fuel burn for the box-wing compared to the conventional configurations because the box-wing offered an improvement in structural efficiency while drastically reducing the aerodynamic penalty for that during those missions.
- Up to a 5% reduction in fuel burn is possible if the box-wing configuration is optimally design compared to conventional for the right mission.

8.3 Recommendations for Future Work

The box-wing configuration definitely offers significant improvements over the conventional if the right mission is considered. However, there are definitely several areas of configuration that need further research before it can be considered a viable and reliable alternative when it comes to actual manufacturers.

Primarily, this has been a conceptual and preliminary design analysis with several assumption and crude methods used for efficiency of design space exploration and analysis of several different configurations. The next step is to undertake detailed design of the configuration from the optimal design points, utilising tools such as computation flight dynamics in order to find important factors such as the zero-lift drag. More intensive FEA models that incorporate the fuselage and other components of the aircraft would allow for more accurate weight breakdowns. More loadcases from different phases of flight would also refine the performance and fuel burn analysis over the whole mission.

The other aspect of the aircraft that requires further development and research is validating theoretical and computational results against real-world performance. The first step with this is to design, build and run wind-tunnel scale models of the box-wing in order to certify that the computation tools and results are providing valid answers, and to calibrate those answers further.

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